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Development Center

Ashtabula River, Ohio, Sedimentation Study

Report 4

Numerical Model

by Ronald E. Heath, Allen M. Teeter, Gary E. Freeman, William L. Boyt

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Prepared for U.S. Army Engineer District, Buffalo

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Preface

The report herein describes a numerical model investigation performed at the U.S. Army Engineer Research and Development Center (ERDC) by the Rivers and Streams Branch (RSB) of the Waterways and Estuaries Division (WED), Hydraulics Laboratory (HL). The Coastal and Hydraulics Laboratory (CHL) was formed in October 1996 with the merger of the Coastal Engineering Research Center and HL.

The work was performed between June 1994 and June 1996 as part of a sedimentation study sponsored by the U.S. Army Engineer District, Buffalo. The U.S. Environmental Protection Agency (USEPA), Region 5, is in charge of the overall project. Messrs. Stephen Golyski and Edward J. Hanlon are the project managers at the Buffalo District and USEPA, respectively.

Personnel of WED performed the work under the general supervision of Messrs. R. A. Sager (retired), Acting Director, HL, R. A. Athow, Acting Assistant Director, HL, W. H. McAnally, Jr., Chief, WED, and M. J. Trawle, Chief, RSB. The study coordinator was Mr. Ronald E. Heath. The numerical model investigation was conducted by Dr. Gary E. Freeman and Messrs. Heath, Allen M. Teeter, and William L. Boyt, all of HL. The report was written by Messrs. Heath and Teeter. Mr. Mike Miller assisted in preparation of the report graphics.

At the time of publication of this report, Dr. James R. Houston was Director of CHL, and Mr. Thomas W. Richardson was Acting Assistant Director. Dr. Lewis E. Link was Acting Director of ERDC, and COL Robin R. Cababa, EN, was Commander.

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1 Introduction

Background

The Ashtabula River flows north into Lake Erie at the city of Ashtabula in northeast Ohio. The Federal navigation project in the lower Ashtabula River contains a breakwater-protected harbor in Lake Erie and a navigable waterway extending about 3.2 km upstream to a point approximately 300 m downstream of the 24th Street Bridge (Figure 1). Sediments in the harbor and lower 600 m (2,000 ft) of the river are classified as suitable for open-lake disposal, whereas sediments upstream of the lower 600 m (2,000 ft) of the waterway to the 24th Street Bridge are classified as unsuitable for open-lake disposal. In the harbor and lower 600 m (2,000 ft) of the river, dredging operations are conducted as required to permit commercial navigation. Dredging operations in the remainder of the waterway were suspended in the 1970s, closing the channel to commercial navigation, in response to the increased cost of safe removal and disposal of sediments contaminated with heavy metals, chlorinated hydrocarbons, and polynuclear aromatic hydrocarbons. The waterway is heavily used for recreational navigation. Limited dredging operations were conducted in the reach upstream of the 5th Street Bridge in 1993 to maintain safe navigation conditions for recreational traffic.

Objective

The objective of this study was to determine the potential magnitude and spatial distribution of scour that may occur during an extreme event, such as the 100-year return period flood, potentially causing exposure and dispersal of contaminants buried in the channel bed sediments. This was accomplished by a combination of field data collection and analysis and numerical model studies.

Approach

A field investigation including both long-term automated monitoring and short-term, single event data collection was conducted to characterize

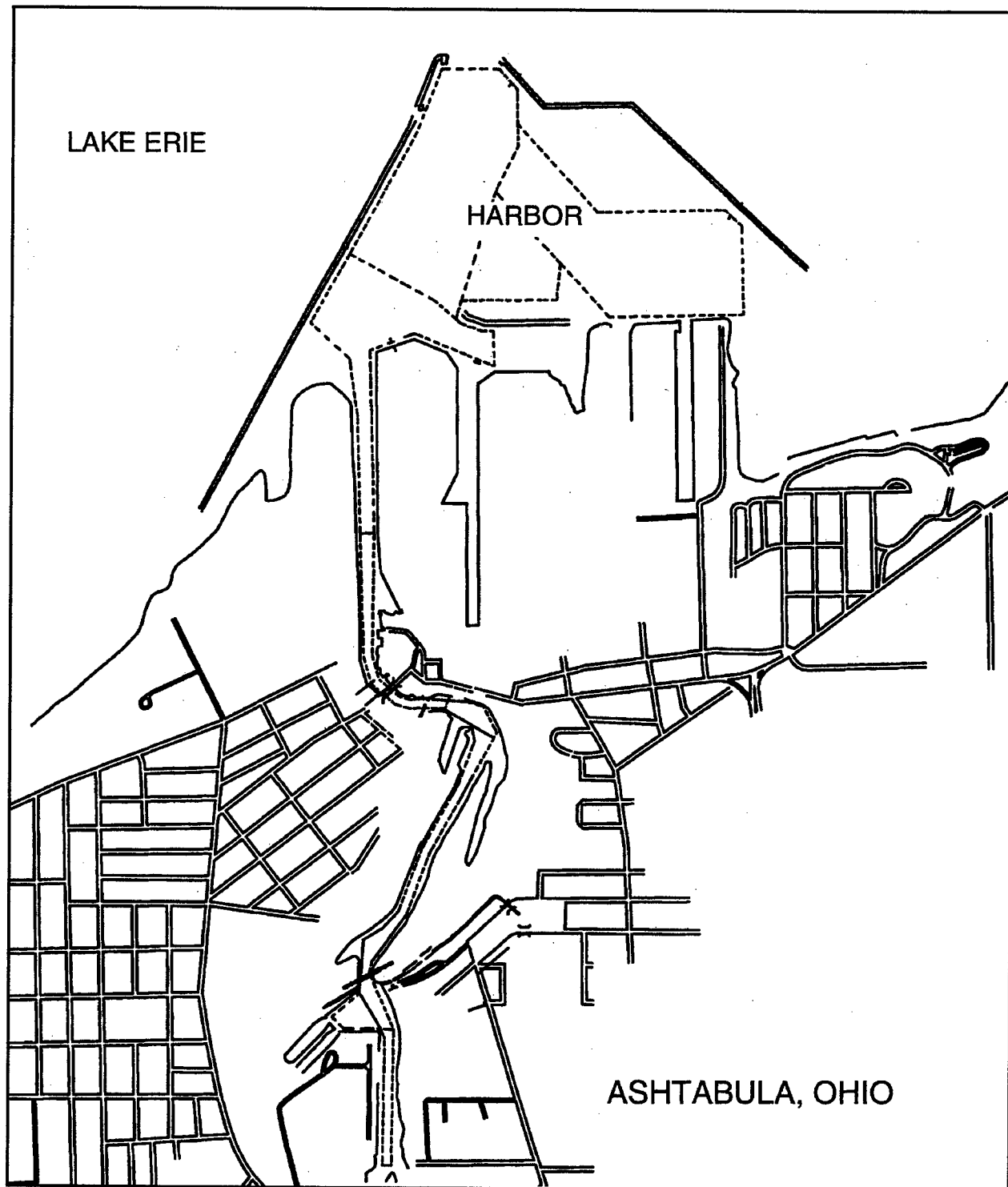


Figure 1. Study area

the hydrodynamic and sedimentation environment within the study area. Laboratory experiments were conducted to determine the characteristics, including erodibility, of bed sediment samples collected from the Ashtabula River. Finally, a numerical model investigation was conducted to

estimate the stresses applied to the riverbed during a hypothetical flood event and the resulting depth and distribution of erosion.

Related Reports

The Ashtabula River and the nature and extent of contamination as estimated from sediment samples collected in 1990 are described in the Ashtabula River Investigation Report.

The U.S. Army Engineer Research and Development Center (ERDC) Cold Regions Research and Engineering Laboratory conducted an investigation of the ice regime of the Ashtabula River (Wuebben and Gagnon 1995). The purpose of that study was to determine if ice processes have a significant impact on channel scour. The results indicated that ice processes are less significant than large open-water flood events, such as the 100-year return period flood event evaluated in this study.

The U.S. Army Engineer District, Buffalo, conducted a hydrologic study of the Ashtabula River Basin to define flood hydrographs for use in this numerical model study.¹

This report is the fourth in a series of reports prepared by the ERDC during this study. The first report documented the status and preliminary results of this study in August of 1994 (Heath et al., in preparation). The second and third reports document the results of the field investigation (Fagerburg 1999) and the laboratory analysis of channel bed sediments (Teeter et al., in preparation).

In a related study conducted by ERDC, the Department of Defense Groundwater Modeling System (GMS) was used to determine and visualize the subsurface distribution and volume of the polychlorinated biphenyl (PCB) contaminant plume within the channel bed sediments.² This study included contaminant data from additional sediment samples collected in 1995. The GMS was subsequently used to determine the volume by concentration of PCB-contaminated bed sediments removed by scour during the worst case scenario for the 100-year return period flood, as described herein, and the resulting surface-area-weighted PCB concentration along the newly exposed bed surface.³

¹ CENCB-PE-PT Memorandum for Commander, U.S. Army Engineer Waterways Experiment Station, regarding "Fields Brook Superfund Site, Ashtabula, Ohio, Discharge Hydrographs for the Ashtabula River" dated 2 Oct 1994.

² Draft CEWES-HH-G Memorandum for: Commander, Buffalo District, regarding "Ashtabula River Contaminant Estimates" dated 29 April 1995.

³ Draft CEWES-CH-G Memorandum for: Commander, Buffalo District, regarding "Data Report on Ashtabula River Contaminant Estimates" dated 23 January 1997.

2 Model Development

Model Selection

The models described herein are process-based numerical models. This type of model uses numerical techniques, such as the finite element method, to find accurate, but inexact, solutions to mathematical equations describing selected physical processes occurring within a system. Conservation of momentum as described in classical physics is an example of such a process. As a matter of efficiency and practicality, simplifying assumptions are applied to the mathematical equations. Selection of physical processes, simplifying assumptions, and numerical techniques, i.e., selection of a model, requires knowledge, experience, and good professional judgment.

To solve these equations for a specific system, the model must include data describing the physical characteristics of the system. This can include both measured data, such as a hydrographic survey, and coefficients inferred by observation of system behavior. Coefficients can also be determined from laboratory experiments or from observation of similar systems. For example, Manning's n -value, a standard empirical coefficient of hydraulic roughness, cannot be measured directly but can be determined from measurements of flow and channel geometry. In the absence of these measurements, there are a number of methods, both empirical and experience based, that can be applied to estimate a reasonable range of Manning's n -values for a specific system.

It is important to recognize that natural systems are variable. Again using Manning's n -value as an example, it is widely recognized that the hydraulic roughness in a river varies with stage and flow. There may also be seasonal variations, short- or long-term changes resulting from natural or man-made variations in the channel geometry or other differences in antecedent conditions. While a numerical model will always produce the same response from a given set of input data, a natural system can be expected to produce at least a slightly different response to very similar events.

While it is obviously desirable to consider natural variability during application of a model, definition and comprehensive evaluation of all potential variations in model input are usually impractical. An alternative is to use professional judgment to identify key parameters and quantify the sensitivity of model response to a reasonable range of values for those

parameters. For example, in the process of designing a channel, an engineer would choose a high estimate of Manning's n-value to predict peak stage and a low estimate to predict peak current speed (overestimating both) to arrive at a "conservative" design.

System Description¹

Upstream of the 24th Street Bridge (Figure 1), the river is confined and relatively steep, and the bed consists primarily of shale bedrock and boulders formed from shale plates. Coarse sediments (sand and larger) from upstream sources are transported through this reach to deposit on the delta or alluvial fan forming in the vicinity of the bridge. Downstream of this location, water levels are dominated by Lake Erie, and the Ashtabula River and Harbor function as a sediment trap for the remaining coarse bedload sediments and finer suspended sediments. The channel reach between the bridge and the upper turning basin, approximately 0.8 km in length, is a sediment-sorting zone where most of the remaining coarse sediment inflow deposits and the bed material transitions to predominately fine (clay and silt) sediment deposits. Without the intervention of continued dredging operations, the coarse bed material deposits will slowly migrate downstream and may eventually alter the hydraulic characteristics and morphology of the river.

The average flow in the Ashtabula River is about 4.2 cms and approaches zero during dry weather. The flow in Fields Brook is augmented by the discharge of process water drawn by local industries from Lake Erie and becomes the primary inflow during dry weather. Snowmelt and rainfall events during the winter and spring are the most frequent source of flood flows, but large floods with a greater than 10-year return period are most likely to be produced by a large convective rainfall event, such as a severe thunderstorm.

Lake Erie stages vary continuously in response to wind- and pressure-driven seiches. The stage variations produce oscillating currents within the river and its associated turning basins and slips. These currents are relatively small compared with those produced by large floods, but probably play a significant role in determining the distribution of fine-sediment deposition within the system. In particular, this forcing could cause a portion of a tributary sediment inflow to be deposited upstream of its source.

The authorized navigation project begins approximately 1,000 ft downstream of the 24th Street Bridge. Downstream to the lower turning basin, the channel is usually confined by high, steep banks on the right (facing downstream), and the left bank consists mostly of sheet-pile retaining walls. Similar retaining walls line portions of the right bank. During the

¹ This description is derived from the lead author's inspections of the site and discussions with field crews and other researchers regarding the site and background information contained in the references identified under the heading Related Reports. Estimated PCB concentrations were derived from the GMS study performed by ERDC.

navigation season, numerous recreational watercraft are docked along the channel. The boats and associated docks are removed during the winter months. The left overbank is subject to occasional flooding primarily caused by ice jams in the vicinity of the 24th Street Bridge coincident with high lake levels.

Fields Brook enters the right side of the upper turning basin from the northeast immediately upstream of the Conrail railroad bridge. The Fields Brook watershed contains the Fields Brook Superfund site and is an active source of contaminated sediments. Strong Brook enters the second of two large slips on the left side of the basin. The geometry of the basin produces a two-dimensional flow pattern where the river currents that are concentrated within the right side of the basin drive counterclockwise circulation within the left side of the basin. The circulation zone tends to trap suspended sediments supplied by the river and Strong Brook, while river currents on the right side of the basin tend to reduce the potential for deposition and increase the potential for scour; thus, deposition tends to be greater on the left side of the basin.

Prior to 1993, the basin was last dredged in 1979, and the accumulated fine sediments are among the most heavily contaminated in the river with typical PCB concentrations near the bed surface ranging from 10 to 40 ppm except at the mouth of Fields Brook where concentrations exceed 50 ppm. Although the vertical distribution of contamination varies widely by location, concentrations tend to increase and then decrease with increasing depth. For example, near the middle of the left side of the basin, PCB concentrations exceed 50 ppm at depths ranging from 2.3 to 3.8 m below the low water datum then decrease to less than 30 ppm at a depth of 5.3 m.¹

The Conrail railroad bridge creates a channel constriction at the downstream end of the upper turning basin. The railroad embankment crosses the floodplain immediately downstream of the turning basin and is of sufficient height to ensure that all flow passes through the bridge opening. The bridge does not obstruct the channel, but accumulation of debris on the abutments and boat fenders could accentuate local scour during a flood event.

Downstream of the bridge, the river bends to the right, deepens, and enters a relatively straight section of channel that extends to the entrance of the lower turning basin at River Mile 1 (about 1.6 km upstream of the mouth). Within this reach, the river tends to meander producing a series of three alternating bars. Significant accumulations of contaminated sediments were found in the first bar downstream of the bridge on the right bank with PCB concentrations exceeding 50 ppm at depths of 2.3 to 5.3 m. PCB concentrations generally decrease downstream through this reach.

Circulation within the lower turning basin is induced both by variations in the level of Lake Erie and by riverine currents. Typical PCB concentrations in the basin are less than 10 ppm. Near the entrance to the lower turning basin, the channel expands then bends sharply to the left and

¹ Unless otherwise noted, all stages and depths are referenced to the low water datum for Lake Erie, which is 173.3 m International Great Lakes Datum (IGLD) 1955.

narrows producing a fourth bar on the inside of the bend. Downstream the channel bends back to the right before entering the deeper commercial navigation channel immediately upstream of the 5th Street Bridge. Within this reach, relatively deep pools are present on the outside of the bends and are connected by a shallower crossing reach at the entrance to the right-hand bend. PCB concentrations range from 1 to 30 ppm at the upstream end of this reach to less than 1 ppm in the vicinity of the bridge.

Downstream of the 5th Street Bridge, the channel and the protected harbor are maintained at an authorized depth of 27 ft (8.2 m) to permit use by deep-draft vessels. Both recreational watercraft within the river and ships within the commercial waterway and harbor can create hydrodynamic forces sufficient to suspend surficial bed sediments. Wind- and seiche-induced currents probably play a major role in determining the distribution of sediment deposition within the harbor.

Model Description

Determination of both the longitudinal and lateral distribution of scour within the study area required the use of a two- or three-dimensional system of hydrodynamic and sediment transport models. A one-dimensional model would not provide information on lateral variations in stage and current speed or induced circulation within the upper and lower turning basins and therefore could not be used to compute the lateral distribution of scour. While a three-dimensional model would provide a more detailed analysis of system hydrodynamics than a depth-averaged, two-dimensional model, use of a three-dimensional model would have significantly increased study complexity and cost. In addition, at the time this study was initiated, three-dimensional sedimentation modeling for fine-grained sediments was still a technology under development.

The model study was conducted using the TABS-MD modeling system, a family of numerical models that provide multidimensional solutions to open-channel flow and sediment transport problems (Thomas and McAnally 1985). The TABS-MD modeling system is the Corps of Engineers' standard for general-purpose modeling of two-dimensional, depth-averaged open-channel flow and sediment transport problems and has been supported by ERDC since the mid-1980s. Appendix A contains an annotated bibliography of publications documenting applications of the TABS-MD system.

The depth and distribution of scour within the study area was computed using the TABS-MD models, RMA-2V and SED2D. RMA-2V is a two-dimensional, depth-averaged hydrodynamic model used to compute water levels and current patterns. RMA-2V employs finite element techniques to solve the Reynolds Form of the Navier-Stokes equations for turbulent flows. SED2D is a companion two-dimensional, depth-averaged sedimentation model used to compute the scour, transport, and deposition of bed sediments. SED2D is an enhanced version of the previous TABS-MD sedimentation model, STUDH.

A common finite-element mesh is used by both models to describe the geometry and spatial distribution of various physical characteristics of the study area, such as Manning's roughness coefficients and bed sediment characteristics. During a simulated flood event, RMA-2V computes a time-history of water depth and depth-averaged velocity at each node in the mesh. These data are used by SED2D to compute a bed shear stress. SED2D compares the bed shear stress with the measured or estimated physical properties of the bed material to compute the sediment transport rate and cumulative scour or deposition at each node.

The ultimate distribution and concentration of bed sediment contaminants depend not only on hydrodynamic and sedimentation processes but also on physical and chemical transformations of the contaminants. RMA-2V and SED2D do not account for these transformations and therefore can provide only qualitative assessments of the fate of the contaminated sediments. Data computed by the hydrodynamic and sedimentation models could be used as input to a contaminant transport model to produce quantitative estimates of the contaminant distribution in the sediment bed and water column during a flood event.

Model Development

A finite element mesh, shown in Figure 2, consisting of 2,982 elements and 8,718 nodes was developed from the 1995 hydrographic survey and National Oceanic and Atmospheric Administration (NOAA) survey chart 14836, Ashtabula Harbor, dated 24 November 1979. Nodal coordinates were referenced to the Ohio state plane coordinate system, North zone. The riverine portion of the mesh is shown in Figure 3. Typical mesh element size in the Ashtabula River was about 30 m longitudinally and 6 m laterally. Bathymetry, shown for the entire mesh in Figure 4 and for the area of interest in Figure 5, was referenced to the low water datum.

In addition to mesh geometry, the hydrodynamic model requires input data describing roughness and turbulent exchange coefficients and initial and boundary conditions. A review of available field data did not produce sufficient information to estimate the roughness coefficient, Manning's n -value. A global Manning's n -value of 0.025 was selected as representative of the relatively smooth, fine-grained bed observed in the river. A global turbulent exchange coefficient value of 366 kg-sec/m^2 was selected by experimentation as providing a reasonable balance between model stability and numerical diffusion. The sensitivity of model results to both roughness and turbulent exchange coefficients was investigated.

For hydrodynamic model simulations of the 100-year return period flood event, two types of boundary conditions were required. At the downstream boundary in Lake Erie, a constant stage was specified. Placement of the downstream boundary in Lake Erie permits hydrodynamic model simulations of time-varying lake levels.¹ Time-varying inflow

¹ The preliminary numerical model investigation indicated that currents induced by fluctuations in the Lake Erie stage were not of comparable magnitude with those produced by flood inflows.

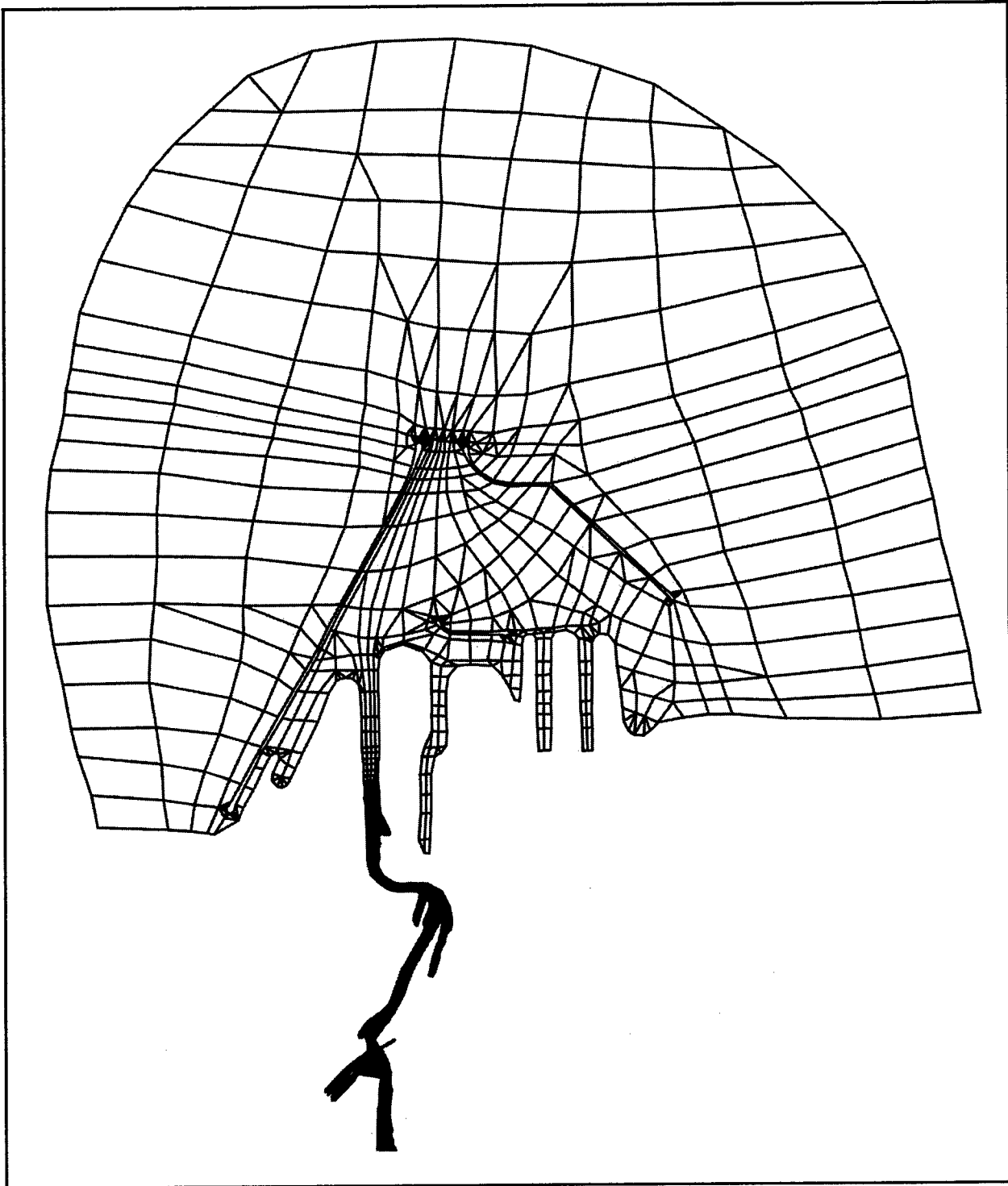


Figure 2. Finite element mesh

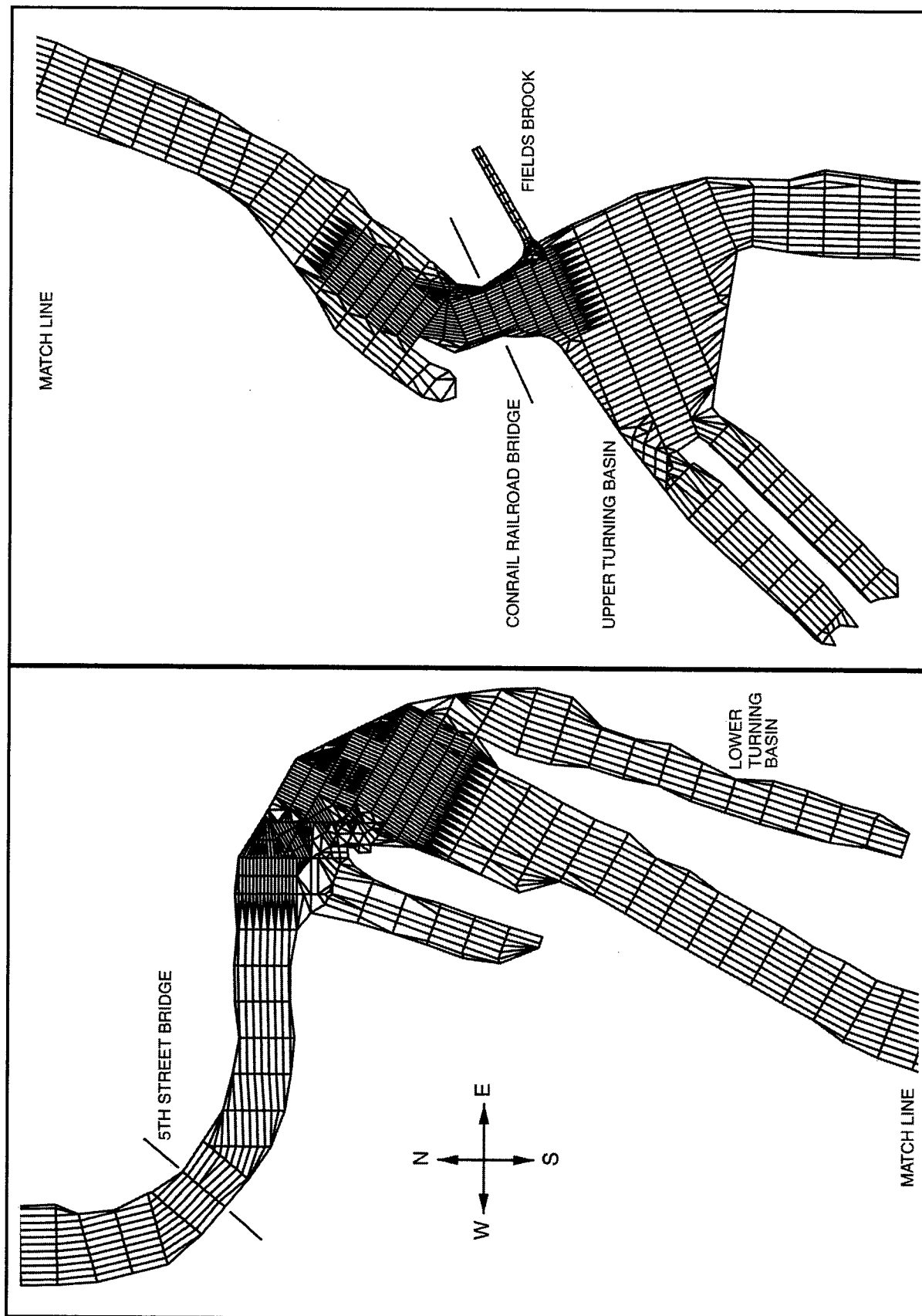


Figure 3. Finite element mesh within area of interest

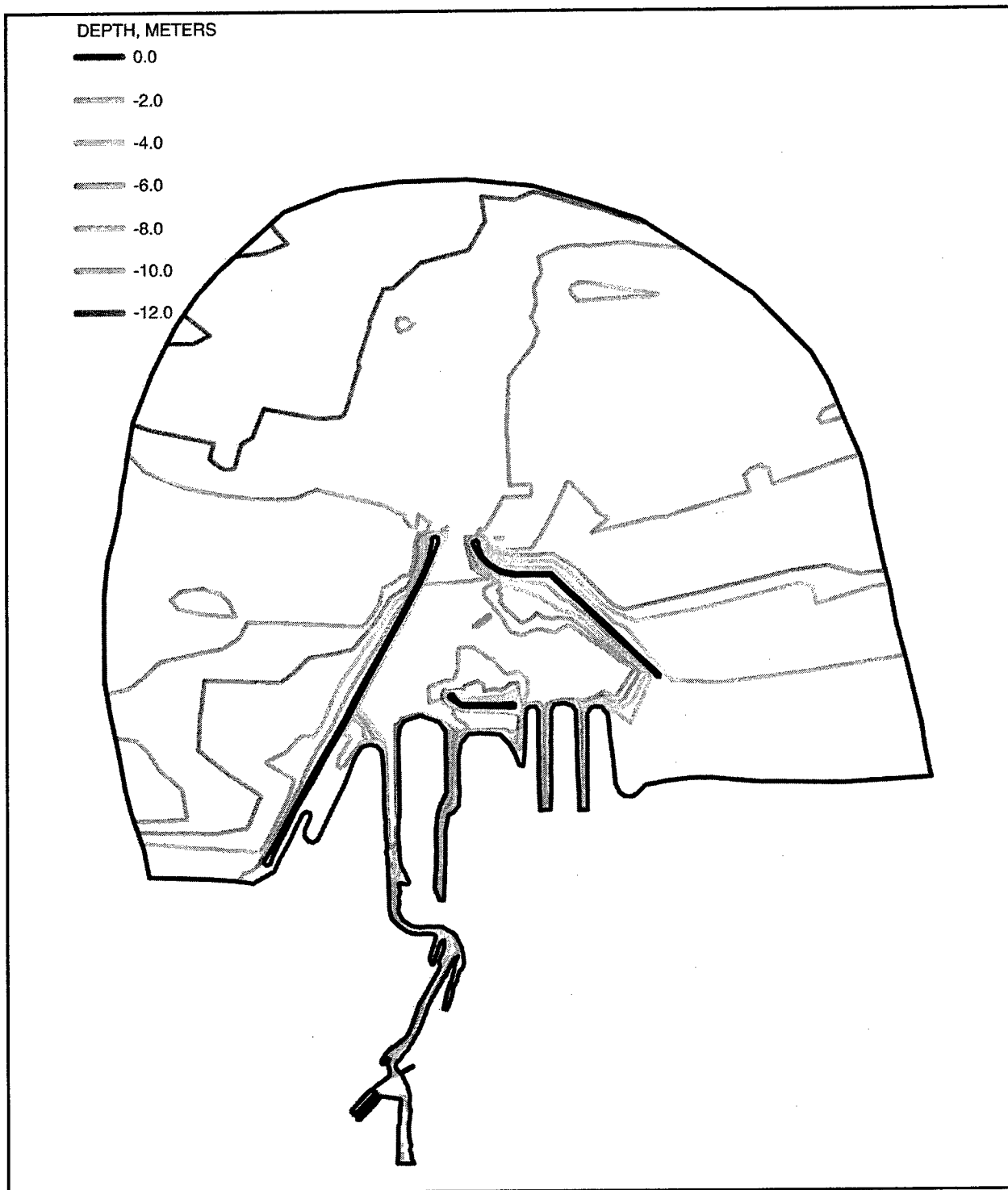


Figure 4. Mesh elevations in meters referenced to the low water datum

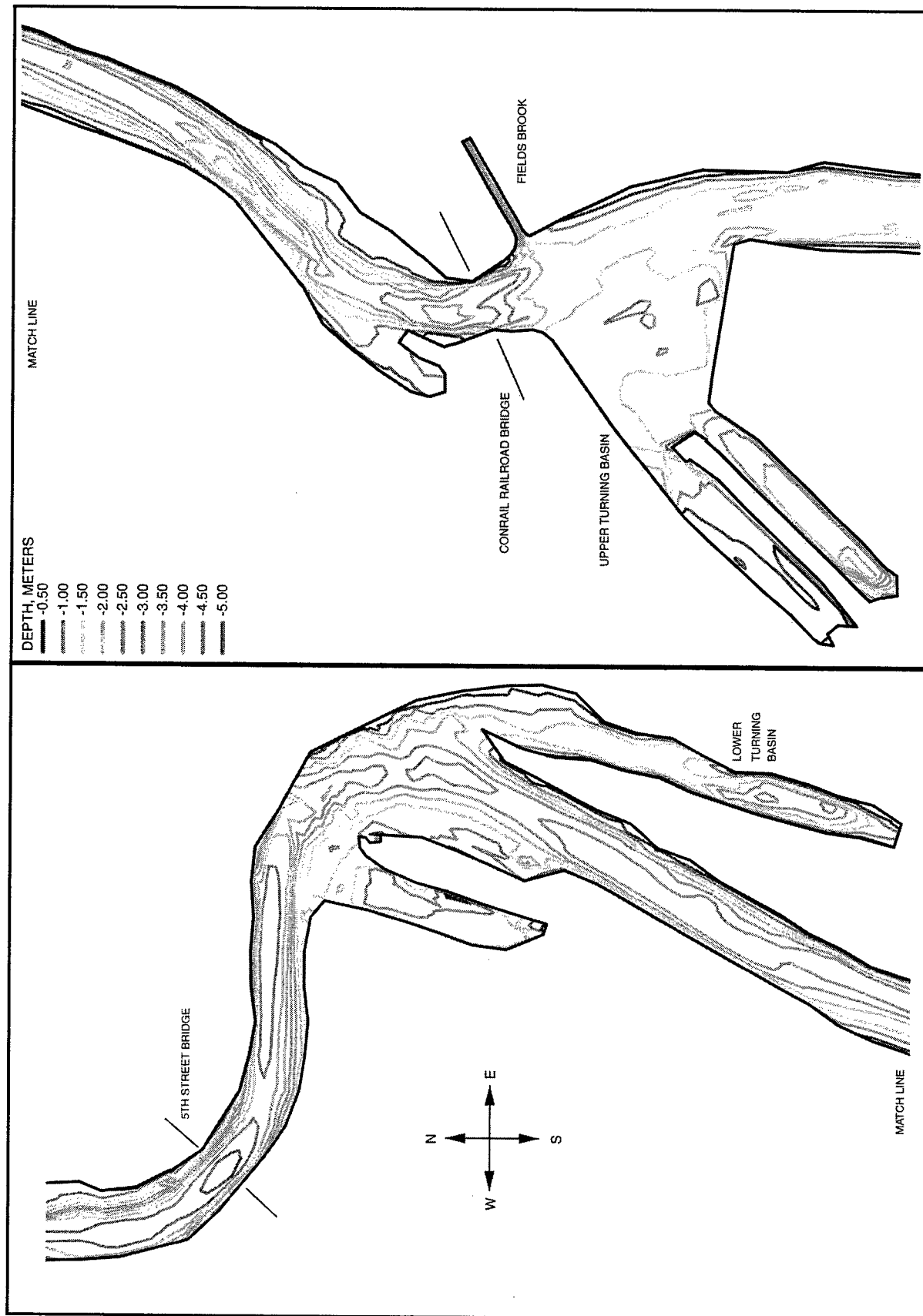


Figure 5. Streambed elevations in meters within area of interest

hydrographs, shown in Figure 6, were specified at the upstream model boundaries of the Ashtabula River and Fields Brook. The boundaries were placed a sufficient distance upstream to ensure that minor errors in the computed distribution of flow at the boundary were not propagated into the area of interest. The initial flow field was developed by computing a steady-flow solution for the first set of inflows used in the flood simulation. Hydrodynamic calculations were performed using a 1-hr time-step.

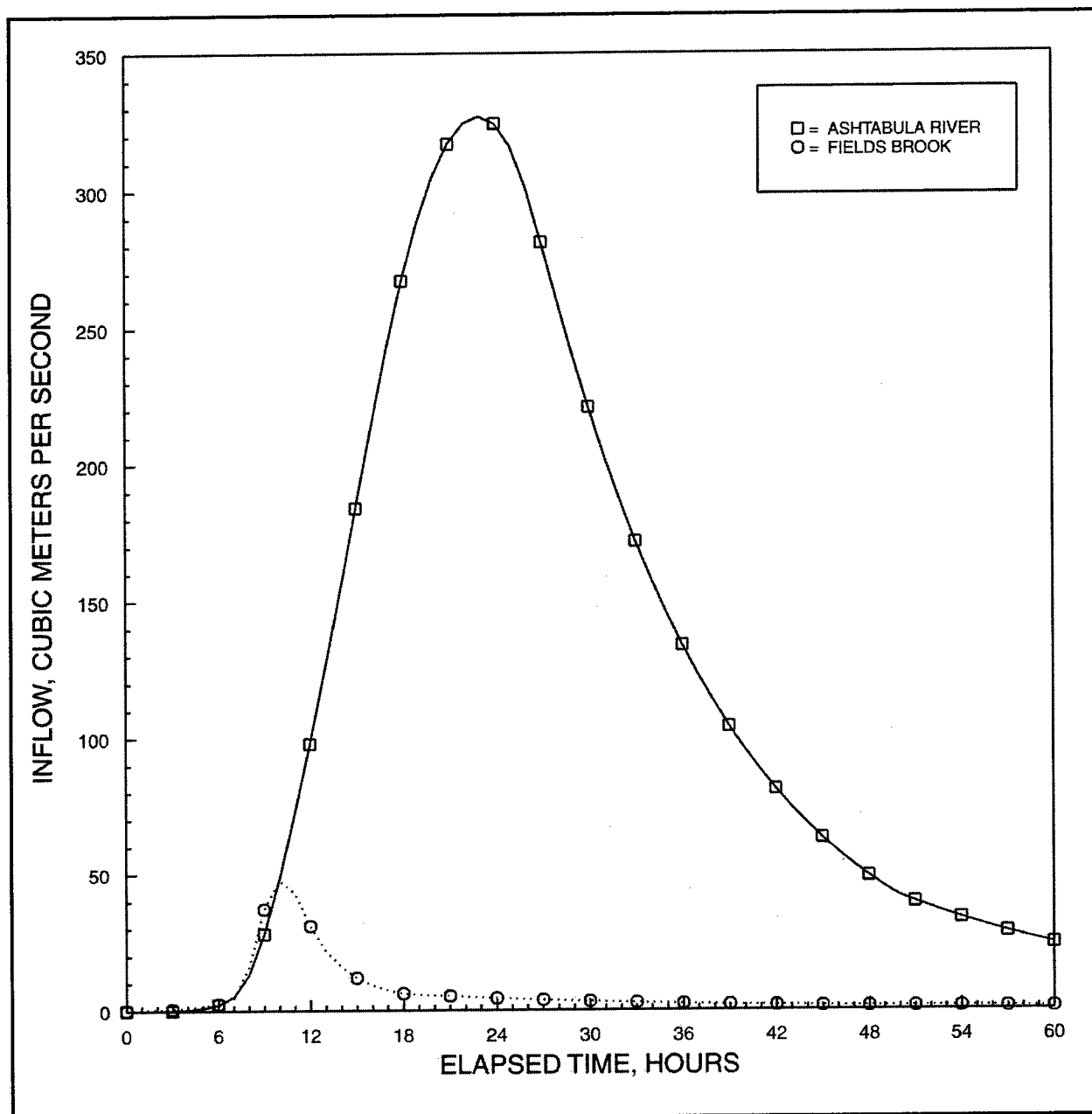


Figure 6. 100-year return period flood hydrographs

The sedimentation model uses a layered bed structure to characterize the density and erodibility horizontally and with depth in the bed. Erodibility of the bed depends on the threshold or critical shear stress for erosion of the material and an erosion rate constant. The erosion threshold controls at what level of applied bed shear stress erosion begins, and the erosion rate constant controls how rapidly sediment layers erode with shear stress in excess of the threshold value. These parameters were determined by erosion experiments and characterization experiments on material from the site (Teeter et al., in preparation). For a certain erosion rate (mass per unit area), the model computes the change in bed elevation based on the dry density of the bed layers.

The modeled bed layers are described in Table 1. Although the sedimentation model permits spatial variation of bed-layer characteristics, a single characterization was used throughout the area of interest because no definable spatial trends were identified during laboratory analysis of the bed material samples. The bed was artificially hardened at the upstream end of the model (an area that contains some coarse sediments) to minimize potential instabilities associated with the distribution of flow at the upstream boundary. The first two layers are representative of the softer surficial sediment deposits that are easily resuspended by wave action or prop wash. The actual thickness of these deposits may vary with location, season, or antecedent conditions. The third layer is representative of the more erosion-resistant subsurface material. For all scenarios, the prescribed thickness of the third layer was greater than the computed scour. The actual thickness is significantly greater and varies with the location of bedrock.

Table 1 Bed Layer Erosional Characteristics				
Layer	Thickness, m	Critical Shear Stress, Pa	Erosion Rate Constant, kg/m²/sec	Dry Density, kg/m³
1	0.005	0.06	0.1	90
2	0.01	0.12	0.01	350
3	3.0	0.28	0.000016	800

The sedimentation model was configured to compute erosion of the bed sediments but not deposition of suspended-sediment inflows or redeposition of the eroded bed sediments. In this mode of operation, the computed bed change at the end of the simulation represents the potential maximum depth of erosion (i.e., negative bed change) throughout the system rather than the net bed change. Since significant deposition (i.e., positive bed change) would be expected to occur both in slack-water areas throughout the flood event and throughout the system as the flood recedes, the net bed change at the end of the event would be greater than the computed bed change.

The sedimentation model computes the general scour distributed over each mesh element based on hydrodynamic model computations of flow and stage. The models account for variations in the flow field and scour patterns produced by longitudinal contractions and expansions. The hydrodynamic computations include a secondary flow or "bendway" correction that accounts for the effects of streamwise vorticity transport on the velocity distribution at river bends (Bernard and Schneider 1992). However, the sedimentation model does not compute local scour produced by acceleration of the flow in the immediate vicinity of an obstruction, such as a bridge abutment or piling supporting a pier. The model does not account for bank failures, nonerosive subsurface failures and subsequent movement of bed materials, or bankline migration.

3 Model Results

Base Simulation Results

Model simulations of the 100-year return period flood were conducted for three different Lake Erie stages as described in Table 2. All comparisons of model results are made to the "worst case" condition where the stage was held constant at the low water datum. By definition, the Lake Erie stage can be expected to equal or exceed the low water datum approximately 90 percent of the time.

Table 2 Downstream Boundary Conditions	
Description	Lake Erie Elevation Meters IGID 1955
Low water datum	173.3
Average water level (from NOAA chart 14836 of 24 Nov 79)	174.3
Extreme high water (from NOAA chart 14836 of 24 Nov 79)	174.8

Case 1 - Low water datum

The computed stages within the area of interest at the time of peak inflow from the Ashtabula River, 25 hr after the start of the simulation, are displayed as a contour map in Figure 7. The peak stage in the upper turning basin was only about 1 ft higher than the average Lake Erie stage, and the entire flood event was confined to the waterway within the area of interest. The corresponding flow field is displayed as a velocity vector map in Figure 8. Comparisons of the computed flow field to the 1995 hydrographic survey revealed that the high velocity thread through the bendways downstream of the upper turning basin followed the channel thalweg with the highest velocities in each bend being computed in the deepest reach of the channel. These results indicate that the secondary flow correction in the hydrodynamic model produced a significantly more accurate computation of flow distribution through the bendways than would have been obtained using a depth-averaged hydrodynamic model without the correction.

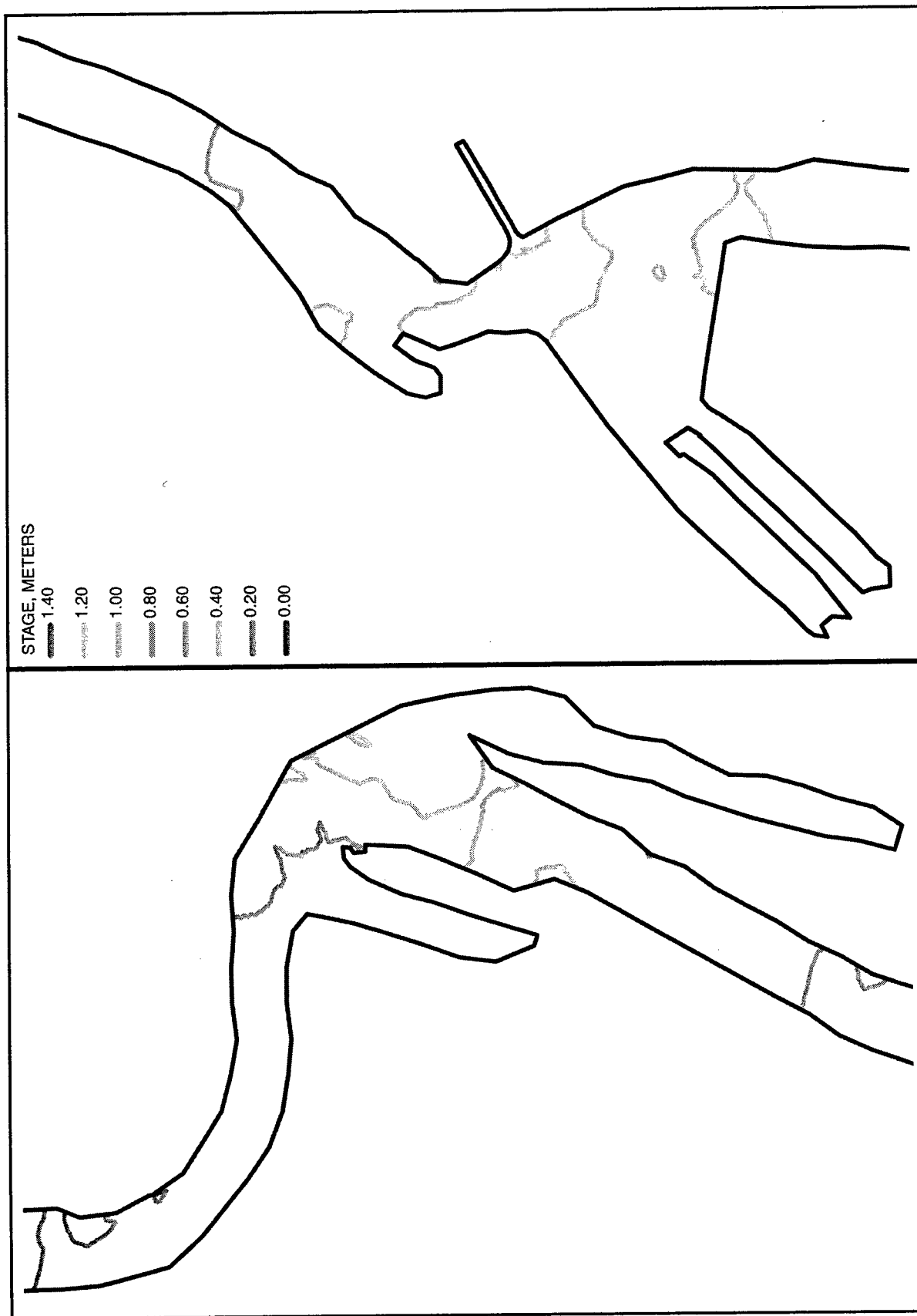


Figure 7. Peak stage in meters within area of interest

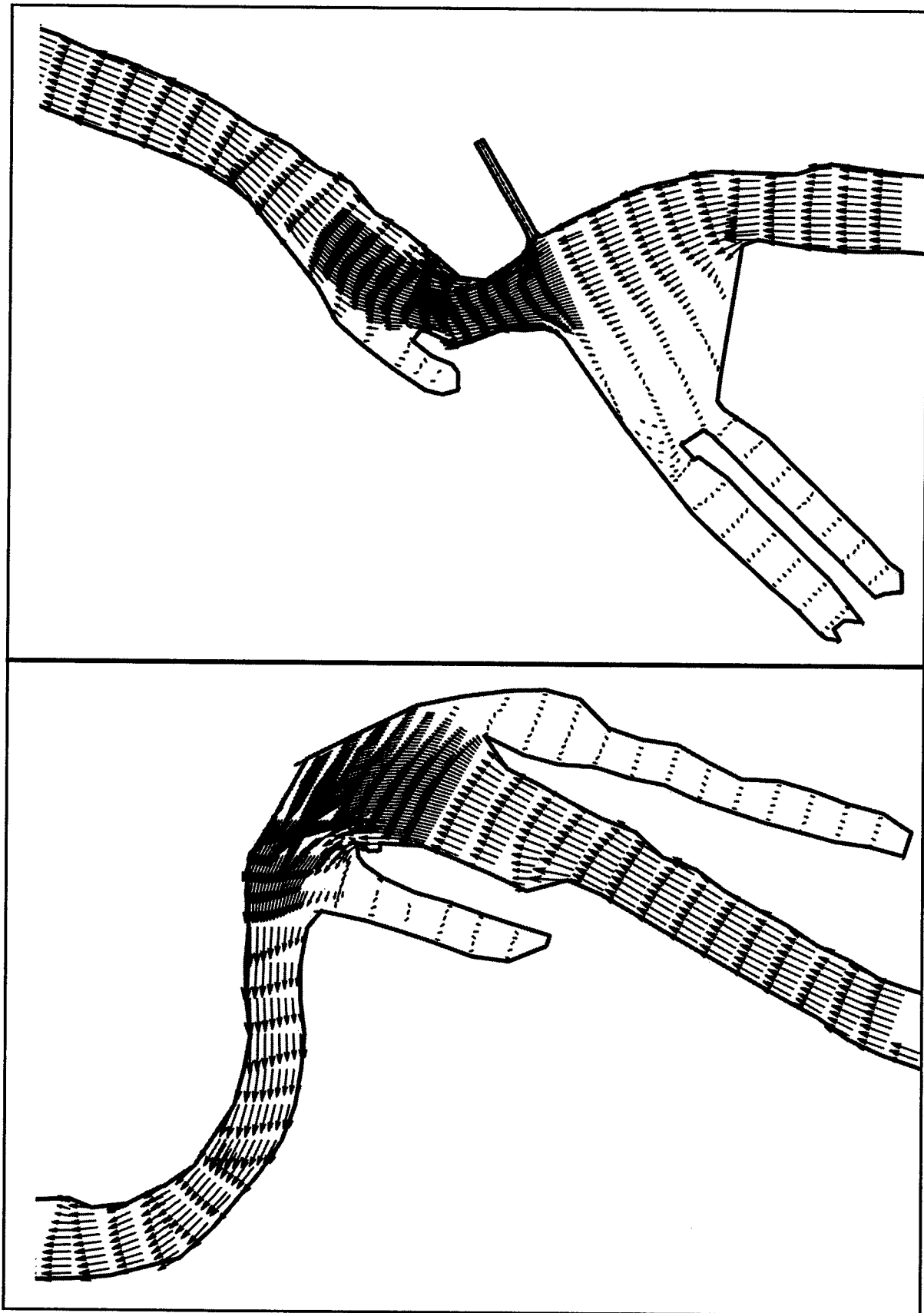


Figure 8. Current pattern within area of interest

The temporal variation of computed stage and other quantities are displayed as a series of hydrographs at selected locations defined as Gages 1-4 in Figure 9. The stage and current speed hydrographs at each gage are shown in Figures 10 and 11, respectively. Peak current speeds at Gage 2 in the right side (facing downstream) of the upper turning basin were 20-30 percent lower than at Gages 3 and 4 in the relatively narrow and deep channel downstream. In contrast, induced currents in the left side of the upper turning basin, as demonstrated by Gage 1, were relatively small throughout the flood event.

Figure 12 is a contour map of peak bed shear stress computed by the sedimentation model at Hour 25. Bed shear stress is a function of both water depth and velocity and is generally higher in the regions of highest current speed (e.g., relatively narrow and deep channels), lower in expansions (e.g., the upper turning basin), and nearly zero in slack-water areas. As shown in Figure 13, peak bed shear stress at Gage 2 was 30-45 percent lower than at Gages 3 and 4, while at Gage 1, the computed value never exceeded the critical shear for erosion.

The cumulative bed change contours at Hour 60, the end of the simulation, are shown in Figure 14. The maximum computed erosion was usually less than 10 cm throughout the area of interest. Upstream of the upper turning basin, erosion typically ranged from 6 to 10 cm. In the upper turning basin, erosion ranged from near zero in the left side of the basin to 4 to 7 cm in the right side of the basin. Immediately downstream of the basin in the vicinity of the railroad bridge, erosion ranged from 5 to 10 cm with small areas of erosion up to 15 cm in the relatively shallow region along the right bank. In the relatively straight reach downstream to the lower turning basin, erosion was typically in the range of 7 to 10 cm. Downstream of the lower turning basin to the 5th Street Bridge, erosion decreased to 5 to 8 cm with larger amounts of scour occurring where flow impinges on the outer bank downstream of the bends. For all cases, erosion in the commercial navigation channel rapidly decreased downstream of the bridge reaching a value of about 1 cm at the mouth of the river, and no significant erosion was computed in the harbor or the lower turning basin.

Given the very small magnitude of the computed erosion, the distribution shown in Figure 14 should be interpreted as a tendency for lesser or greater scour within different regions of the channel and not as a precise estimate of relative scour between adjacent locations. As shown in Figure 15, the soft surficial sediment layers (with an estimated total thickness of 1.5 cm) were rapidly removed when the bed shear stress exceeded the critical shear stress for erosion approximately 9 hr into the simulation. This event exposed the denser, more erosion-resistant underlying sediments that continued to erode at a rate proportional to the bed shear stress as shown for Gage 2 in Figure 16.

Case 2 - Average Lake Erie stage

The stage contours produced by increasing the Lake Erie stage approximately 1 m to its average level are shown in Figure 17. The higher stage

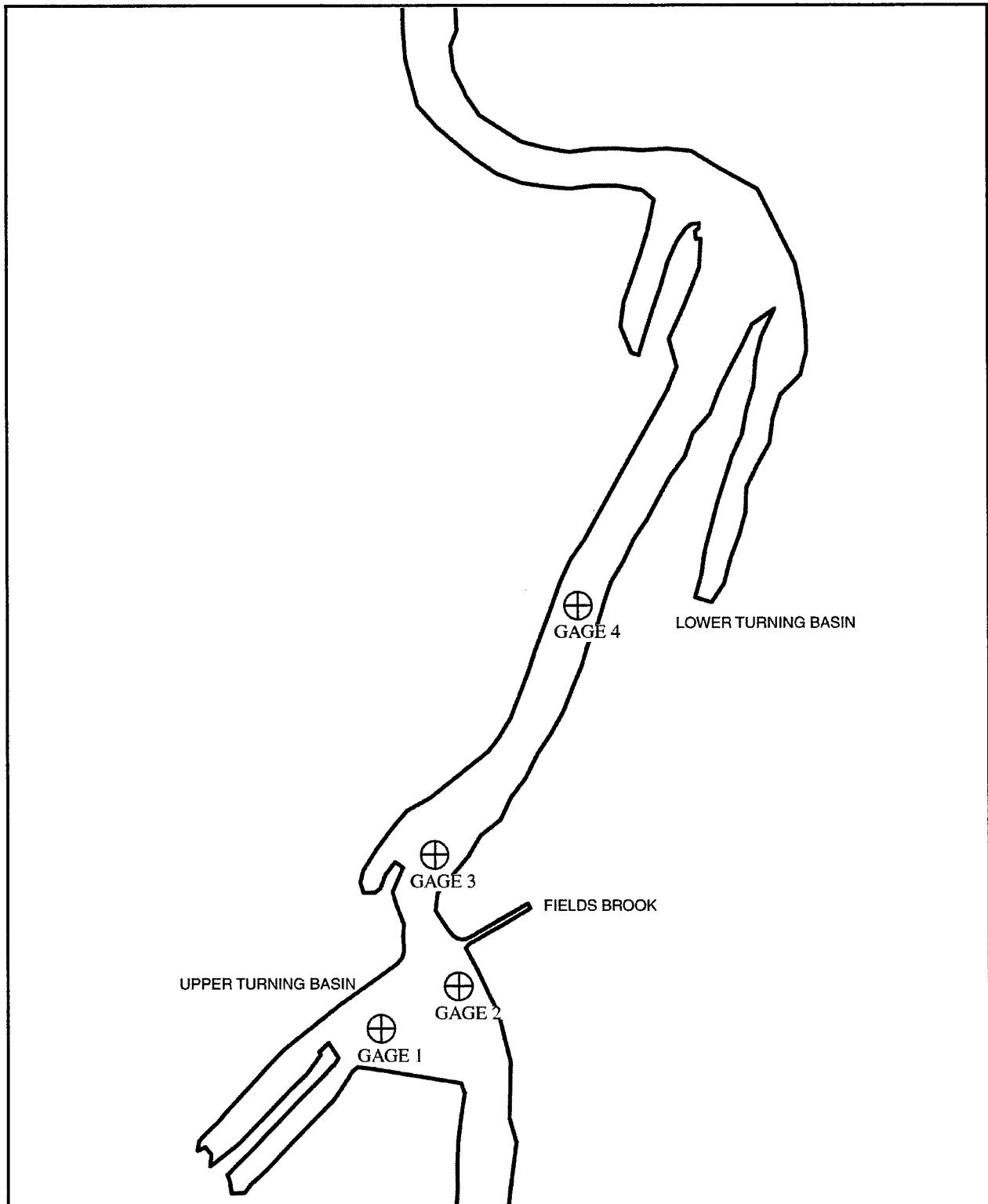


Figure 9. Gage locations

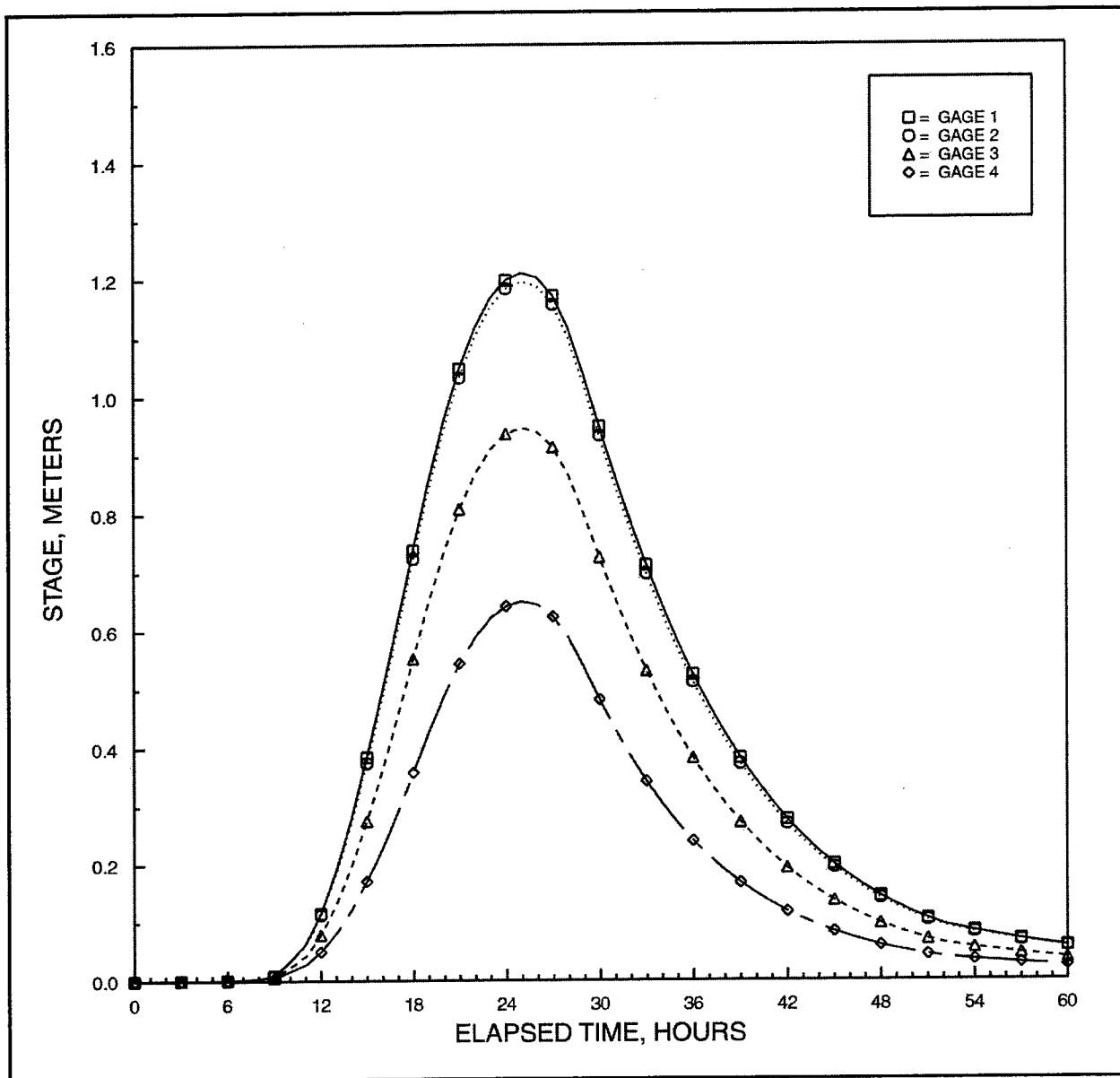


Figure 10. Stage hydrographs

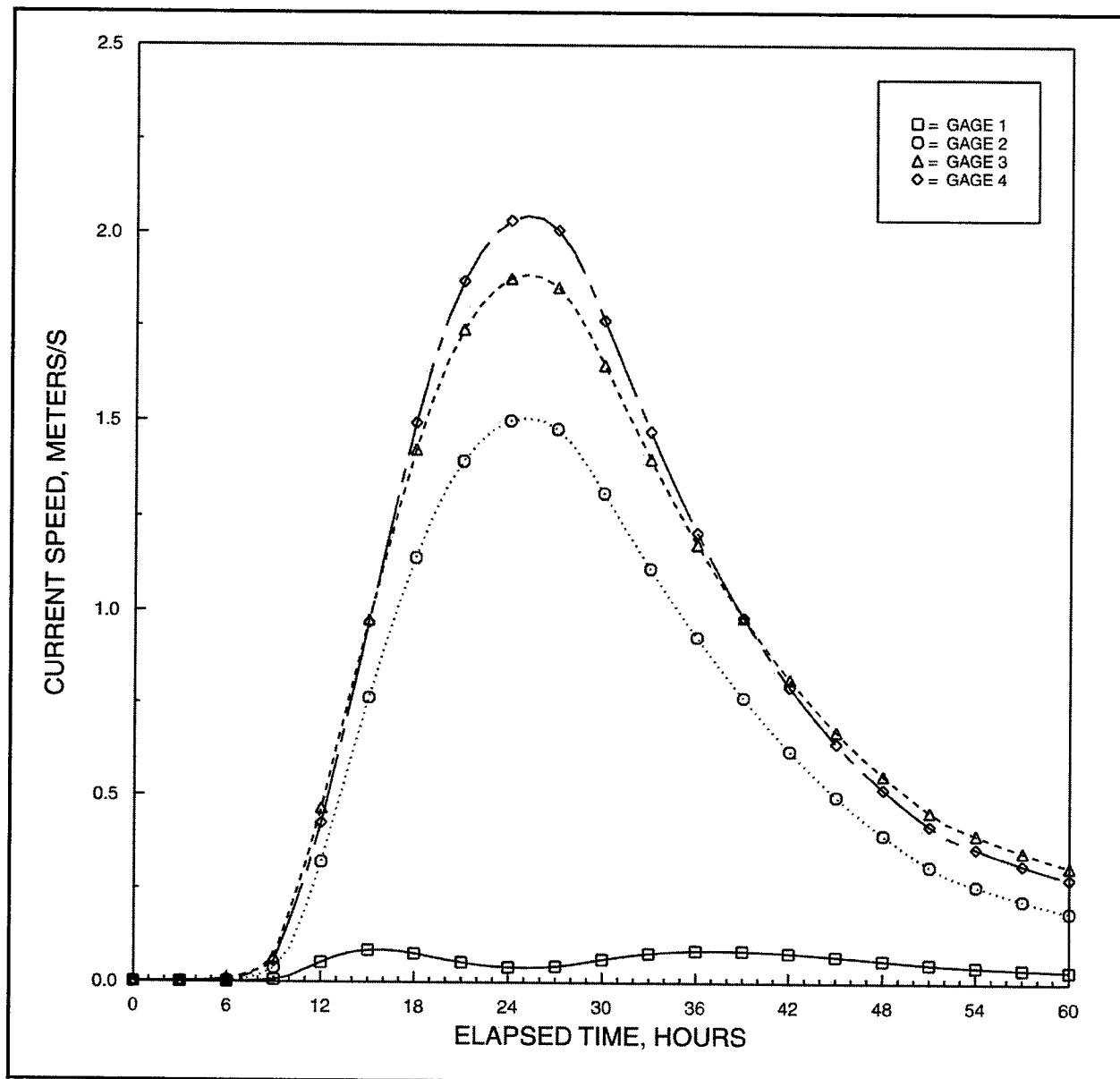


Figure 11. Current speed hydrographs

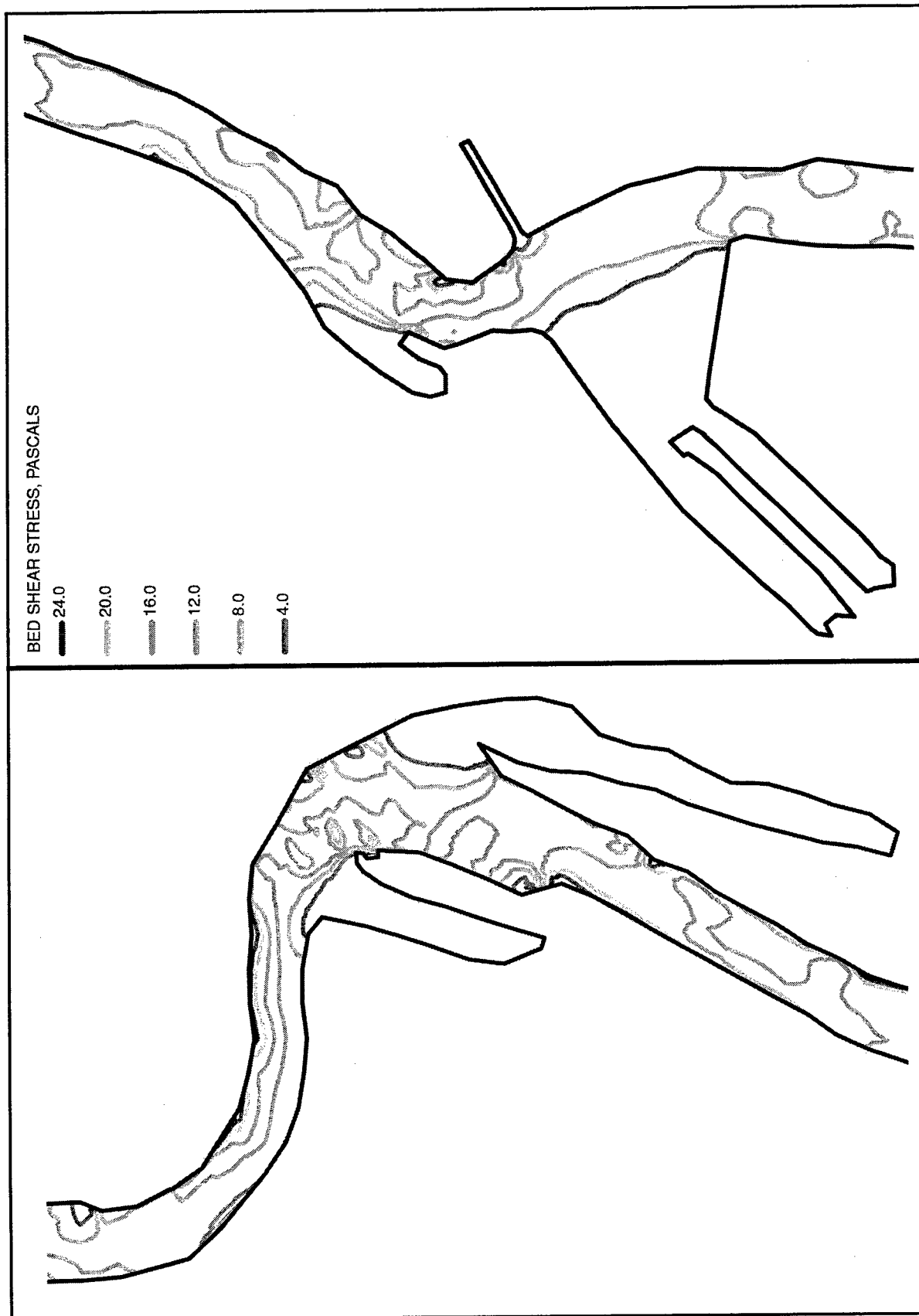


Figure 12. Bed shear stress in Pascals within area of interest

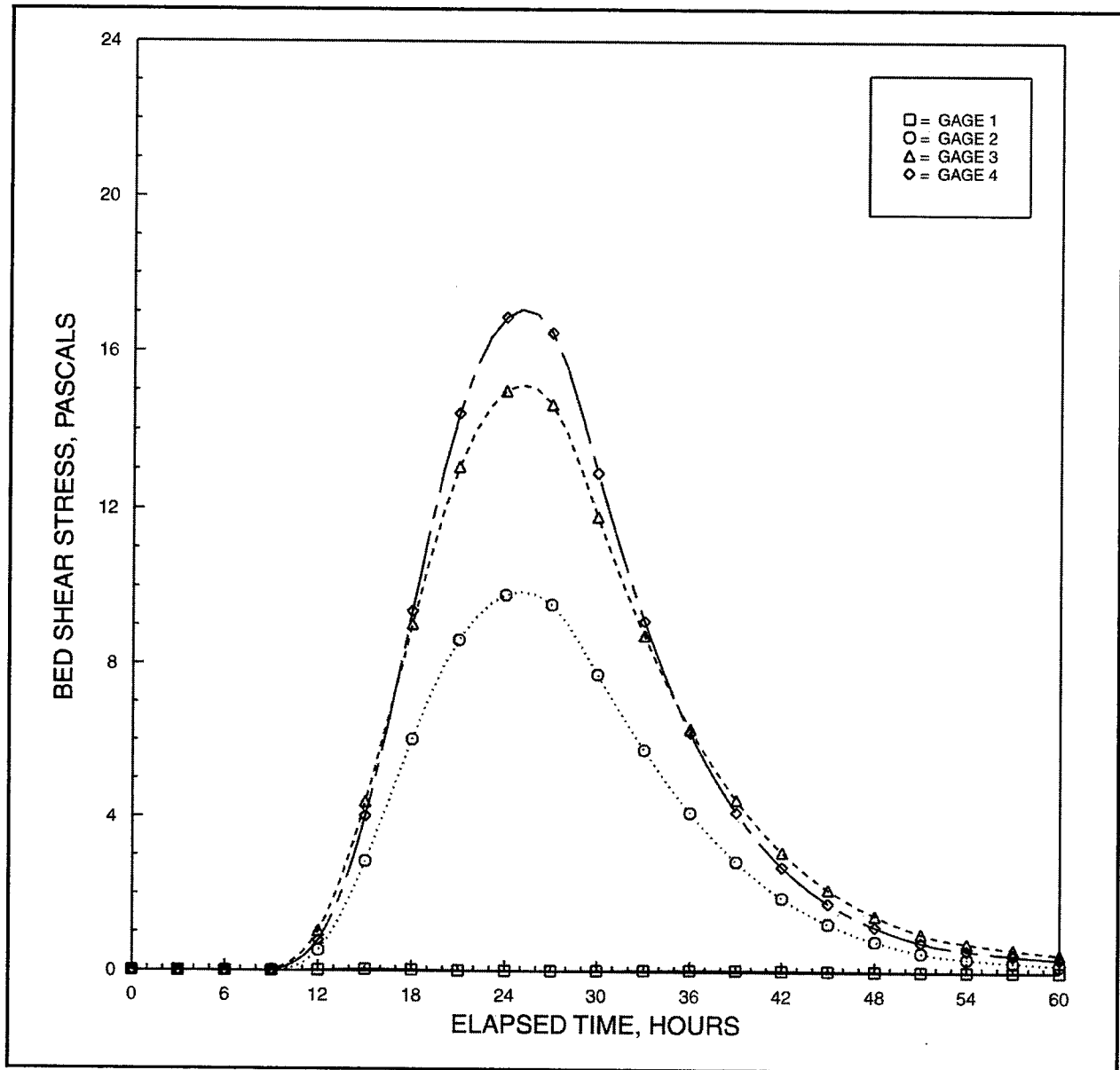


Figure 13. Bed shear stress hydrographs

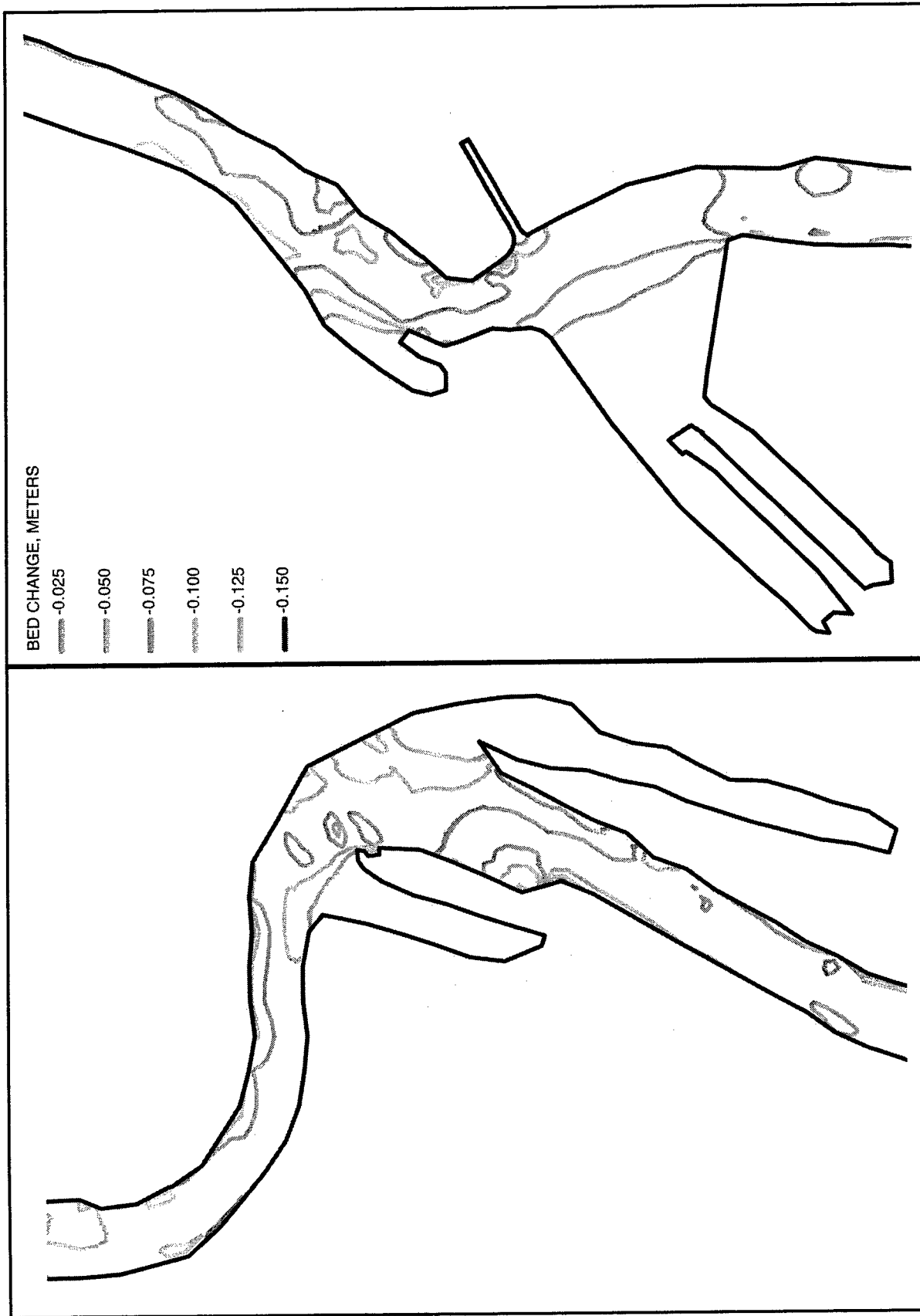


Figure 14. Accumulated scour in meters within area of interest

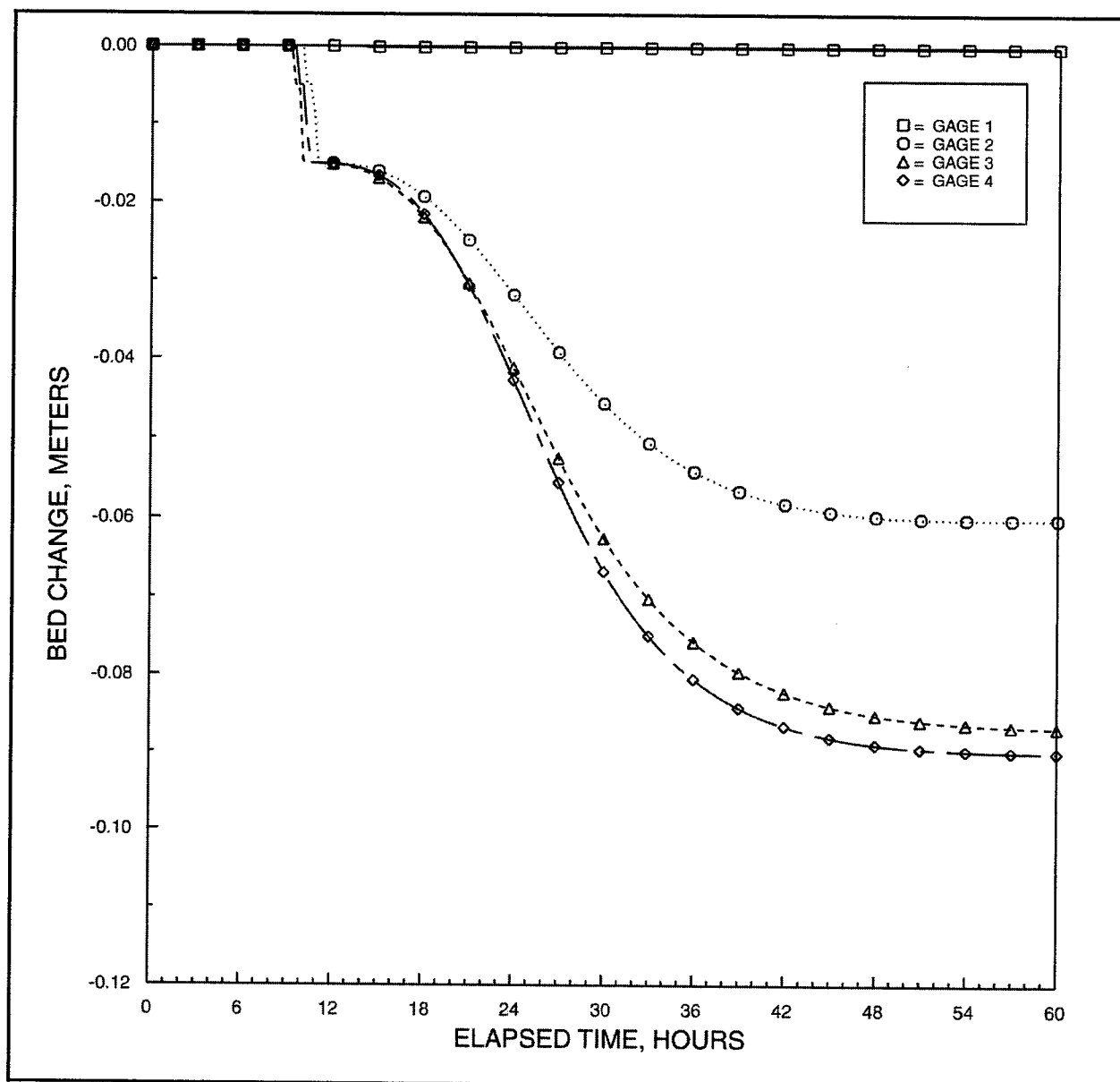


Figure 15. Accumulated scour hydrographs

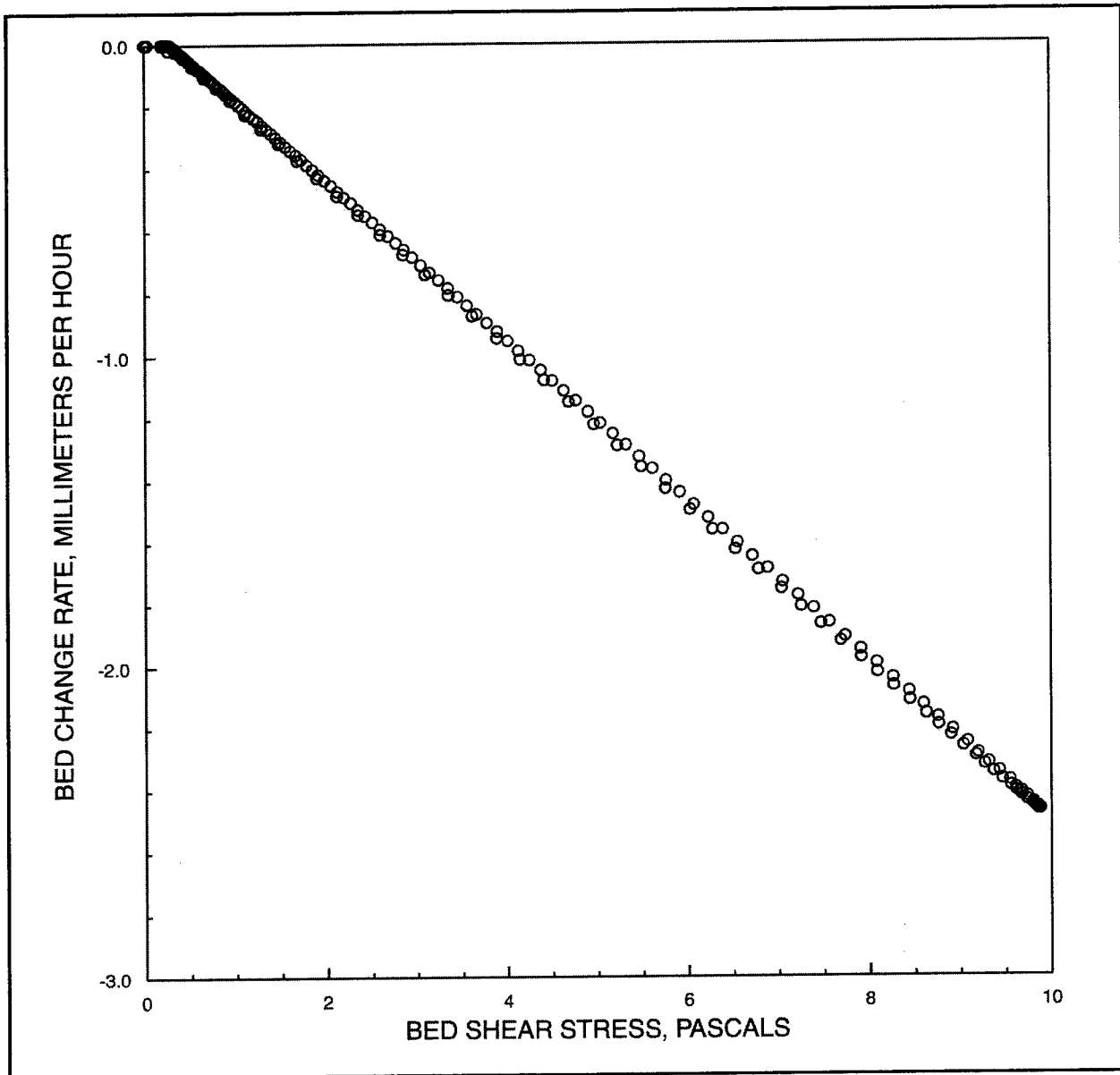


Figure 16. Erosion rate as a function of bed shear stress

increased channel conveyance causing a reduction in water surface slope and corresponding reductions in current speeds, bed shear stress, and bed change, which are demonstrated in Figures 18-20. For example, at Gage 3, the increase in stage resulted in a 15-percent reduction in peak current speed and produced a 30-percent reduction in peak bed shear stress.

The cumulative bed change contours for Case 2 are shown in Figure 21. Upstream of the upper turning basin, erosion ranged from 4 to 7 cm. In the upper turning basin, erosion ranged from near zero in the left side of the basin to less than 5 cm in the right side of the basin. Immediately downstream of the basin in the vicinity of the railroad bridge, erosion ranged from 4 to 7 cm with small areas of erosion up to 10 cm along the right bank. In the reach downstream to the lower turning basin, erosion was typically in the range of 4 to 6 cm. Downstream of the lower turning basin, erosion gradually decreased to less than 4 cm in the commercial navigation channel downstream of the 5th Street Bridge. As compared with Case 1, the total scour from the streambed was reduced by about 30 percent.

Case 3 - High Lake Erie stage

Increasing the Lake Erie stage by about an additional 0.5 m produced additional decreases in current speed and bed shear stress as demonstrated in Figures 18-20. The cumulative bed change contours are displayed in Figure 22. Upstream of the upper turning basin, erosion ranged from 3 to 6 cm. In the upper turning basin, erosion ranged from near zero in the left side of the basin to less than 4 cm in the right side of the basin. Immediately downstream of the basin in the vicinity of the railroad bridge, erosion ranged from 3 to 6 cm with small areas of erosion up to 7 cm along the right bank. In the reach downstream to the lower turning basin, erosion was typically in the range of 4 to 5 cm. Downstream of the lower turning basin, erosion gradually decreased to generally less than 3 cm in the commercial navigation channel downstream of the 5th Street Bridge.

As compared with Case 1, the total scour from the streambed was reduced by about 40 percent. It should be noted that the effects of dredging significant portions of the navigation channel would be similar to increasing stage in that the total volume of scour would be reduced, with the most significant difference being that dredging would tend to concentrate the flow and the resulting scour in the dredged channel instead of dispersing flow across the entire waterway. However, comparisons of computed bed shear stresses for bathymetry before and after the 1994 interim dredging from a preliminary model study did not reveal significant variations in the magnitude or distribution of potential erosion (Heath et al., in preparation).

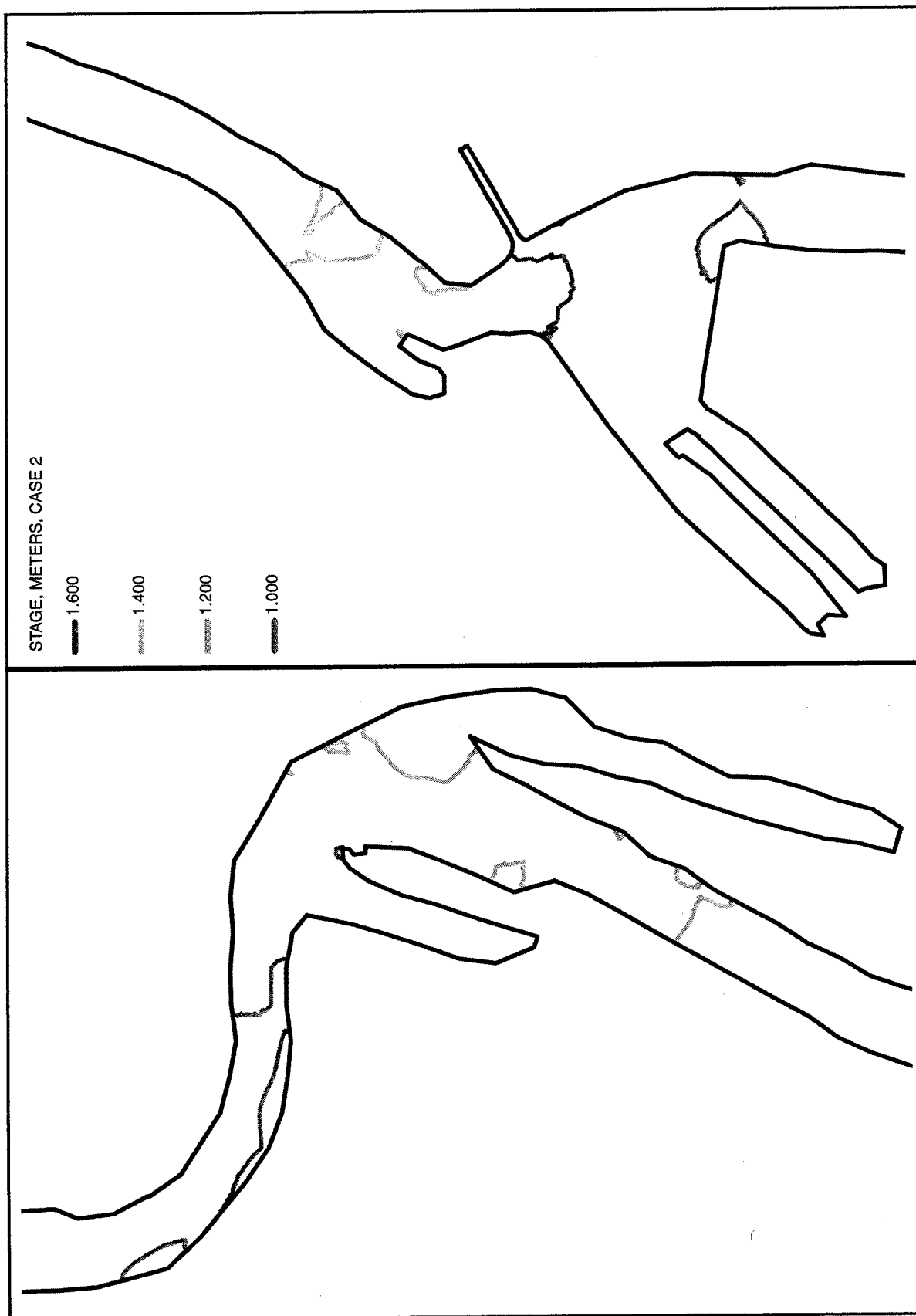


Figure 17. Peak stage in meters within area of interest for Case 2

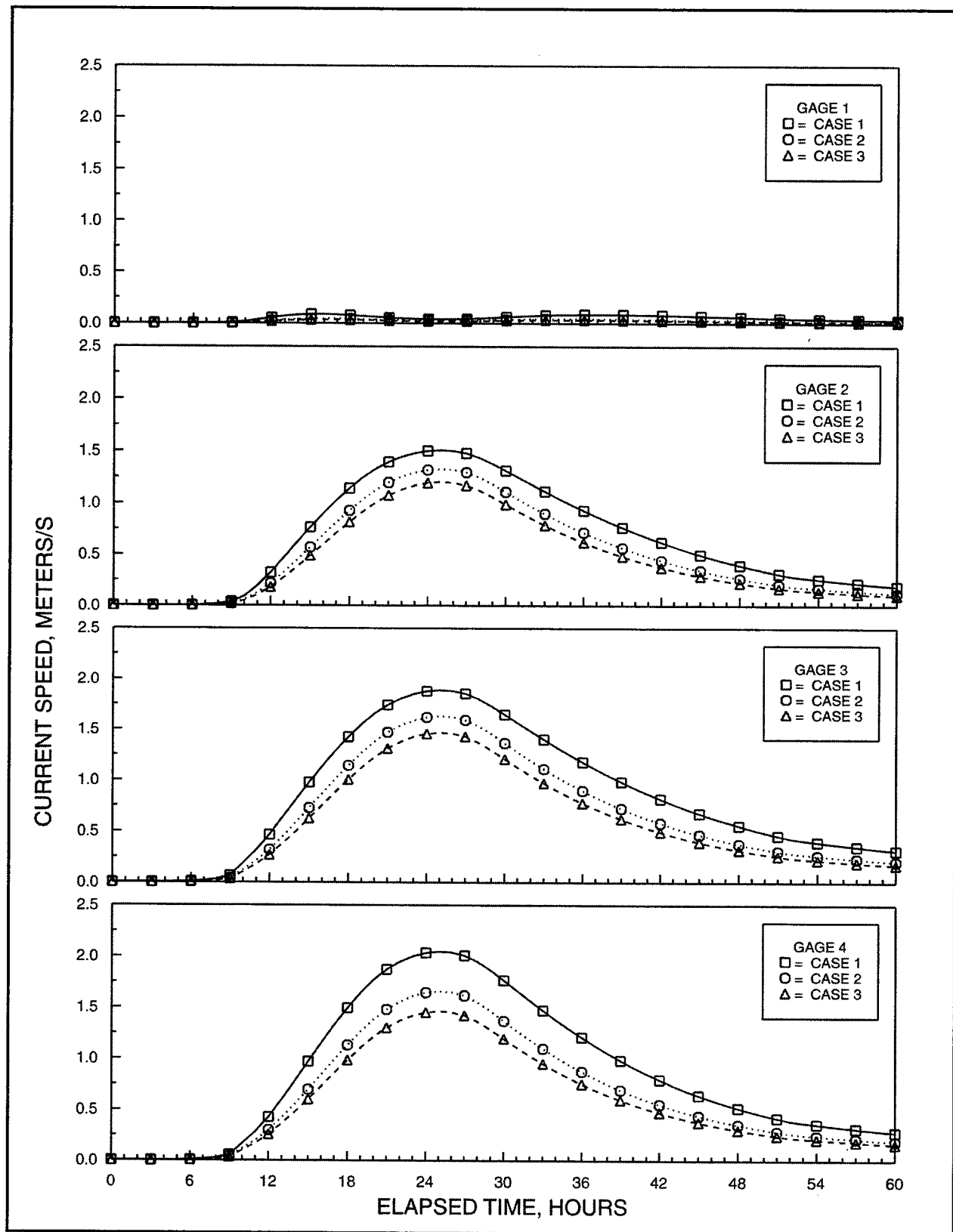


Figure 18. Effect of Lake Erie stage on current speed

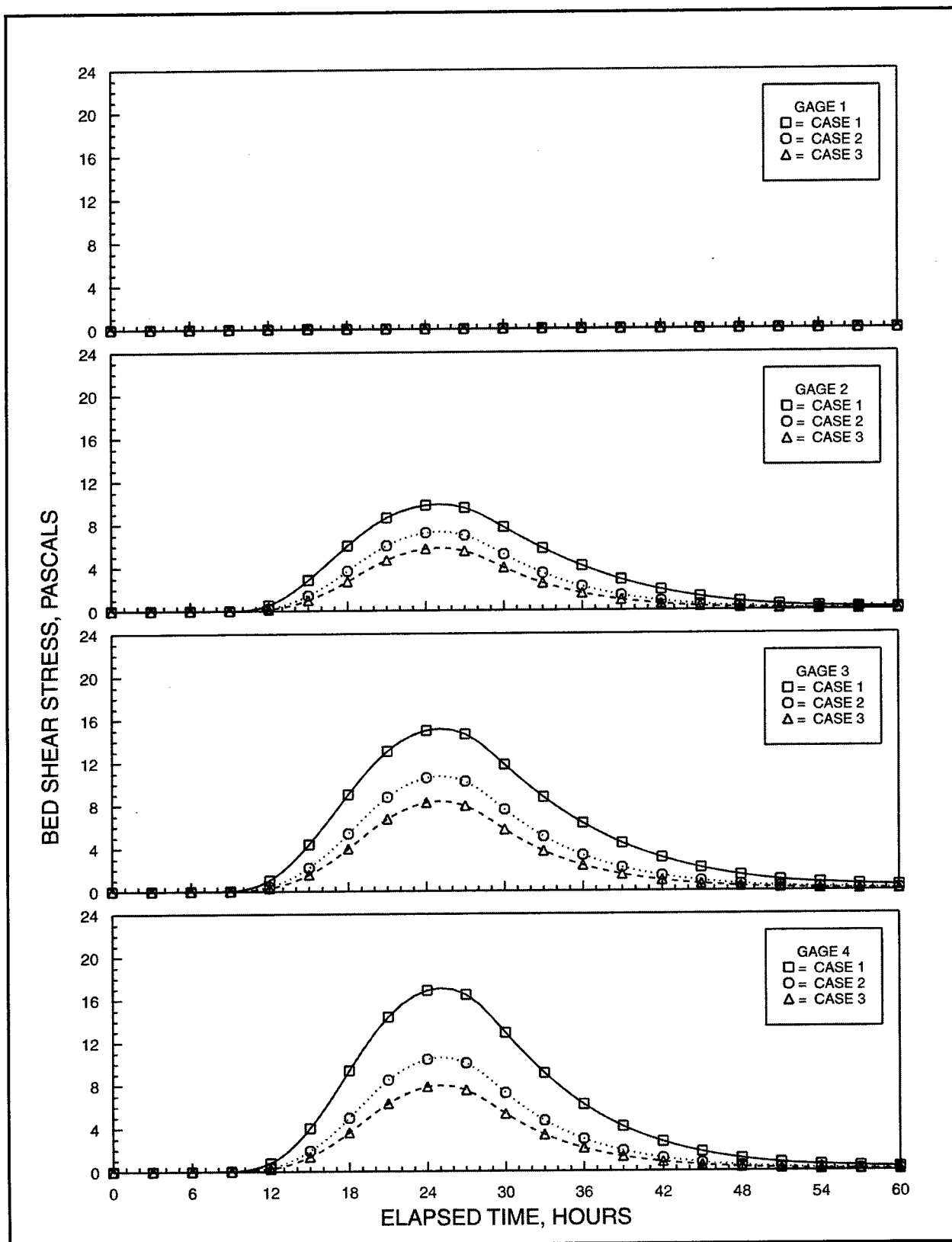


Figure 19. Effect of Lake Erie stage on bed shear stress

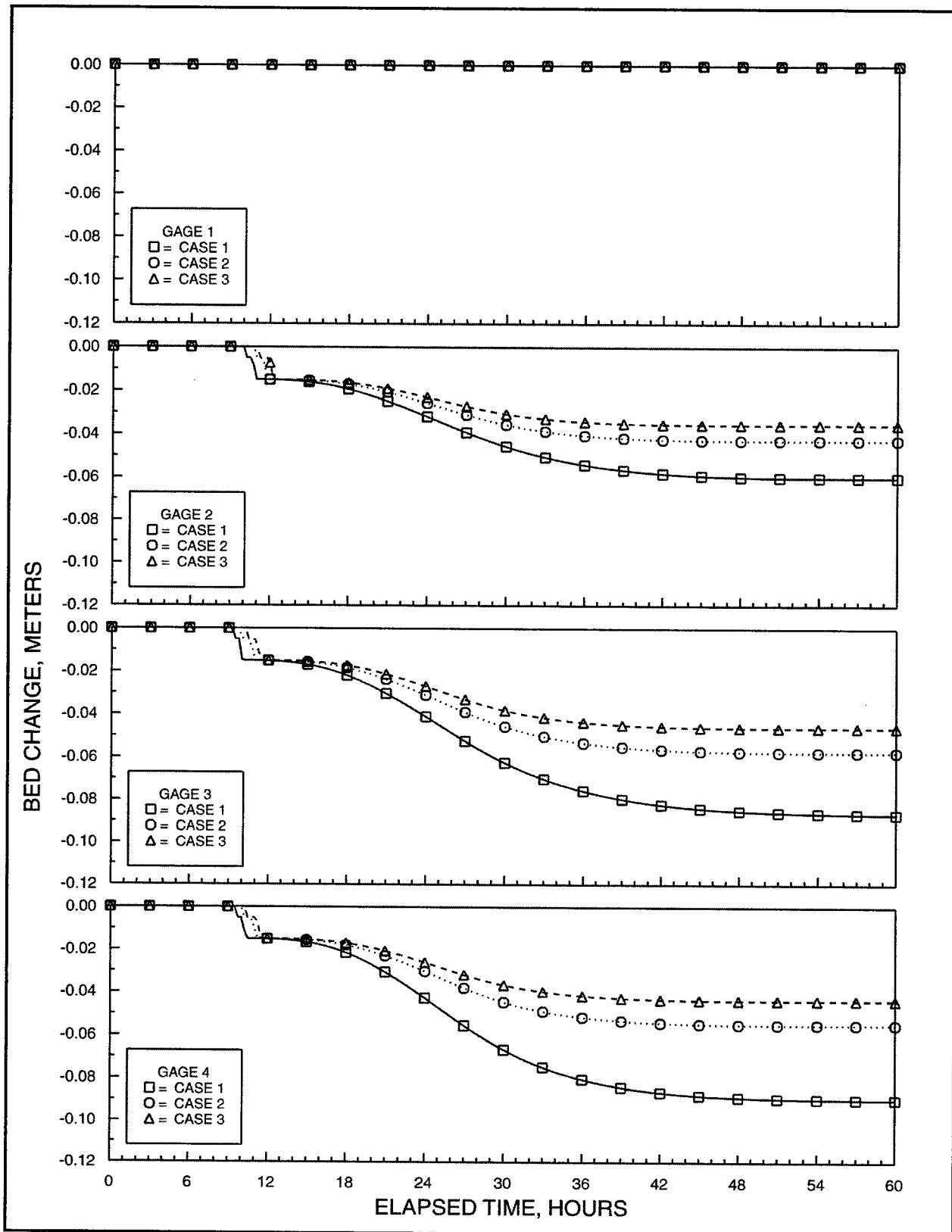


Figure 20. Effect of Lake Erie stage on bed change

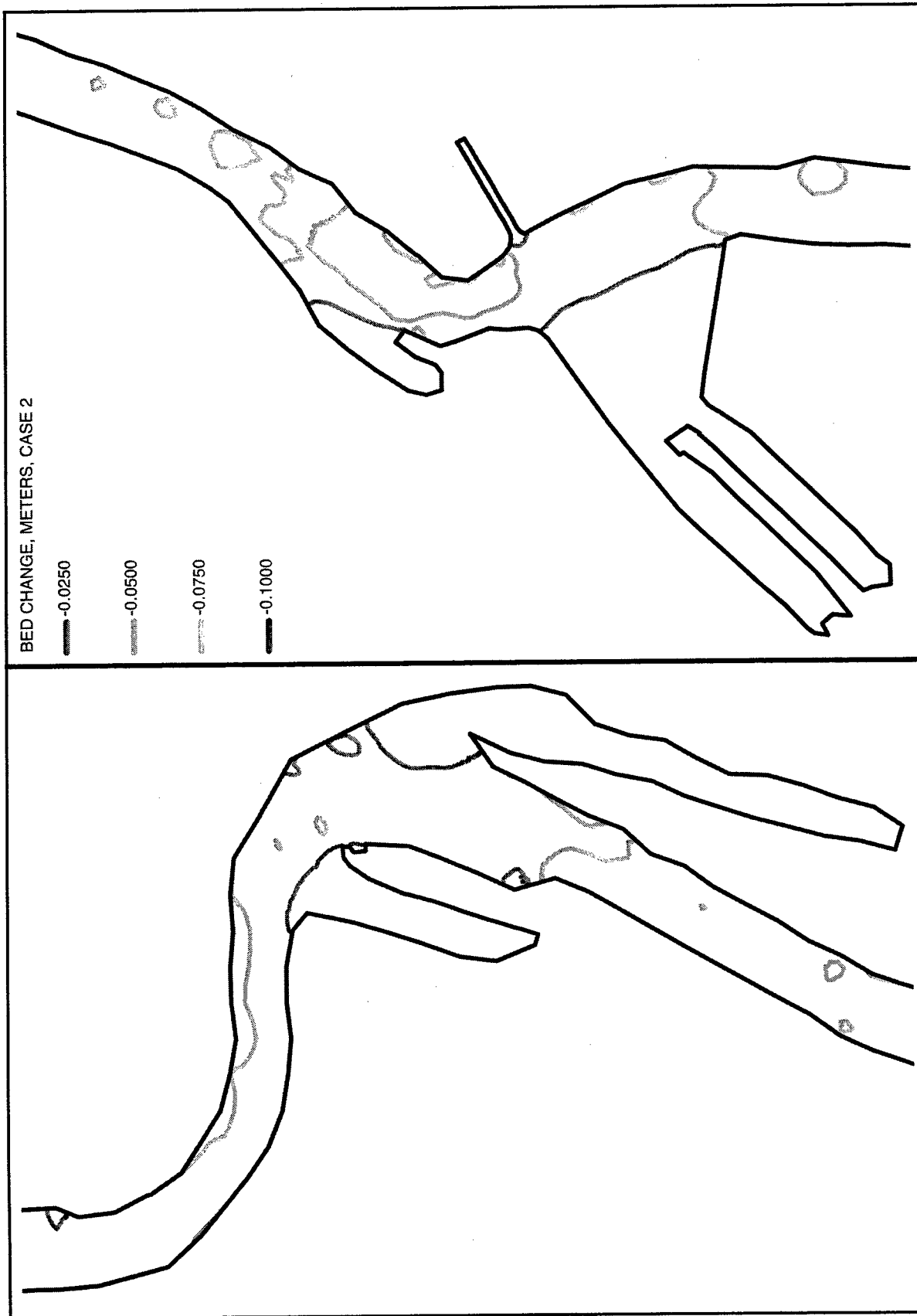


Figure 21. Accumulated scour for Case 2

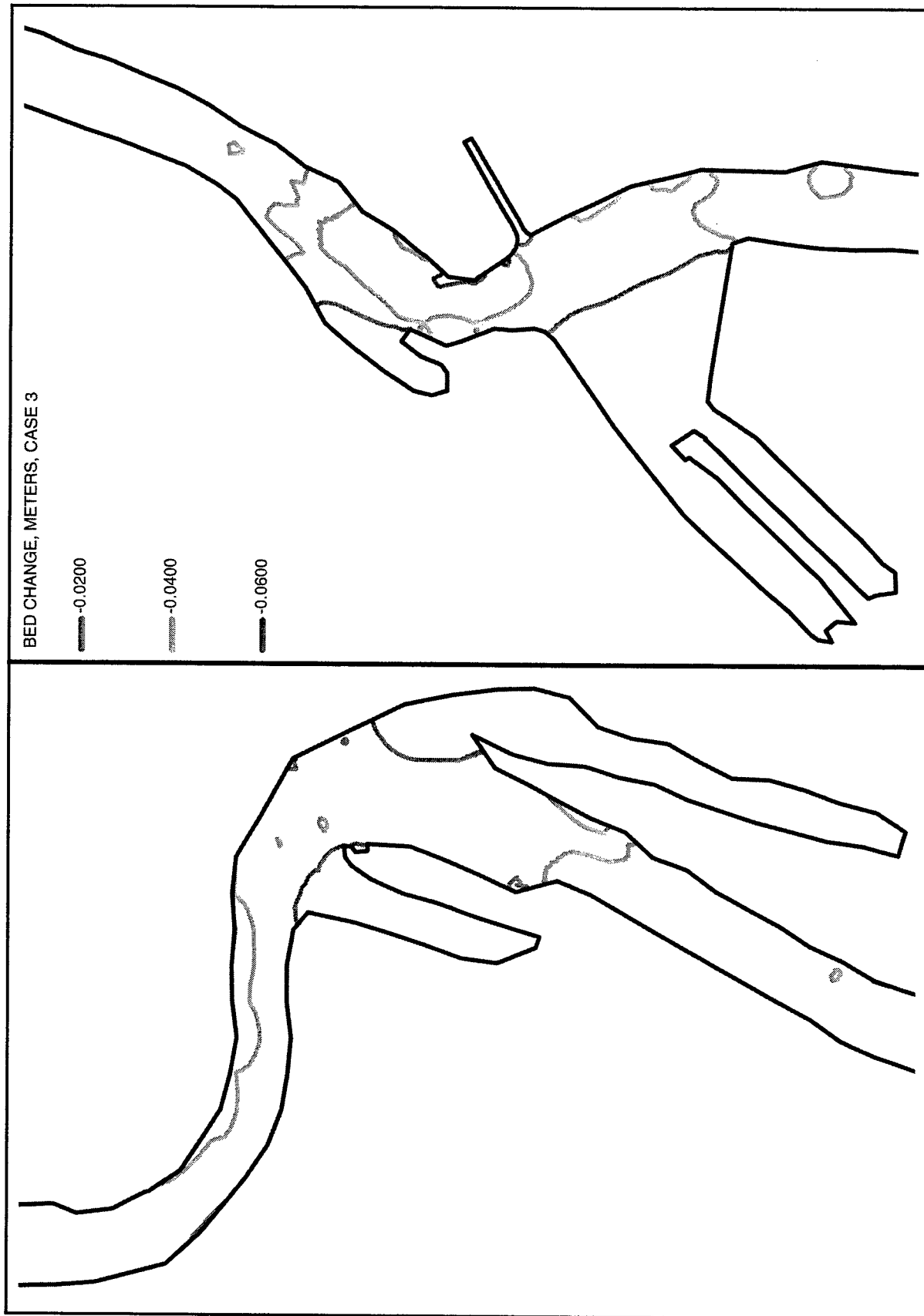


Figure 22. Accumulated scour for Case 3

Sensitivity Experiments

Field data collection and analysis

Numerical model studies are often accompanied by field data collection and analysis studies. These studies may be conducted for a number of reasons including the following:

- a. Measurement of physical characteristics of the system.
- b. Confirmation that model assumptions are reasonable.
- c. Collection of measurements to support adjustment of model coefficients.
- d. Observation of system behavior to determine if model results are reasonable.

A field data collection and analysis study, as documented in Reports 2 and 3 of this series, was planned and executed in conjunction with the numerical model study. The portion of the field study directed at characterizing the bed sediments within the Ashtabula River produced information critical to completion of the numerical model study.

Another portion of the field study was directed at collecting measurements during one or more flood events to support adjustment of model coefficients and to determine the accuracy of numerical model results. Despite a good faith effort to execute that portion of the program, the data collected was not useful for the intended purpose. Flood events on the Ashtabula River are relatively short, with significant flows often occurring for less than 48 hr. Because of the logistical difficulties of mobilizing equipment and personnel to collect detailed measurements onsite during a flood event, automated data collection platforms were installed to supplement whatever data could be collected. Attempts were also made to develop logistical alternatives that, within budget constraints, would increase the probability of collecting the desired onsite measurements. Unfortunately, no significant flood events occurred during the study period, with 1995 being recorded as one of the driest years in the last half-century within the region.¹

No historical data applicable to model adjustment were identified during the study. In the absence of field measurements, professional judgment and experience become the primary factor in selection of model coefficients and evaluation of the accuracy of model results. By testing the sensitivity of the model to a range of coefficient values, the precision of the model results can be quantified.

¹ Personal Communication, August 15, 1996, Stephen J. Golyski, U.S. Army Engineer District, Buffalo, Buffalo, NY.

Roughness coefficient

The sensitivity of the model simulations to the estimated value of the roughness coefficient was tested by varying the value of Manning's n -value by ± 20 percent. Increasing Manning's n -value produces an increase in water-surface slope causing increased stages upstream and lower current speeds. The net effect is higher computed bed shear stresses and more erosion of the bed material. Decreasing Manning's n -value produces changes in the opposite direction. These variations in stage, current speed, bed shear stress, and bed change are displayed in Figures 23-26.

A 20-percent increase in the Manning's n -value to 0.03 produced the cumulative bed change contours shown in Figure 27. Upstream of the upper turning basin, erosion ranged from 7 to 12 cm. In the upper turning basin, erosion ranged from near zero in the left side of the basin to 5 to 8 cm in the right side of the basin. Immediately downstream of the basin in the vicinity of the railroad bridge, erosion ranged from 6 to 12 cm with small areas of erosion up to 17 cm along the right bank. Downstream to the 5th Street Bridge, erosion was typically in the range of 7 to 13 cm. As compared with the base n -value of 0.025, the total scour from the streambed increased by about 23 percent.

A 20-percent decrease in the Manning's n -value to 0.02 produced the cumulative bed change contours shown in Figure 28. Upstream of the upper turning basin, erosion ranged from 5 to 8 cm. In the upper turning basin, erosion ranged from near zero in the left side of the basin to 4 to 6 cm in the right side of the basin. Immediately downstream of the basin in the vicinity of the railroad bridge, erosion ranged from 4 to 10 cm with small areas of erosion up to 15 cm along the right bank. In the reach downstream to the lower turning basin, erosion was typically in the range of 5 to 7 cm. Downstream of the lower turning basin to the 5th Street Bridge, erosion was typically in the range of 3 to 6 cm. As compared with the base n -value of 0.025, the total scour from the streambed decreased by about 20 percent.

The field data that was collected in 1994 and 1995 do not include a runoff event of sufficient magnitude to permit determination of the roughness coefficient from observed stages or velocity profiles. Since the roughness coefficient may vary with changes in flow and water depth, a single determination of its value would not be sufficient to characterize the coefficient for the entire range of flows experienced during a flood event. However, the variations in scour produced by adjusting the roughness coefficient were relatively small compared with the impact of varying the Lake Erie stage.

Turbulent exchange coefficients

Reducing the turbulent exchange coefficient from 366 to 244 $\text{kg}\cdot\text{sec}/\text{m}^2$ increased scour by about 2 percent. Within the area of interest, there were no visible differences in the distribution of scour. Reducing the coefficient to 122 $\text{kg}\cdot\text{sec}/\text{m}^2$ produced numerical instabilities in the sedimentation model, primarily in the relatively shallow portion of the waterway

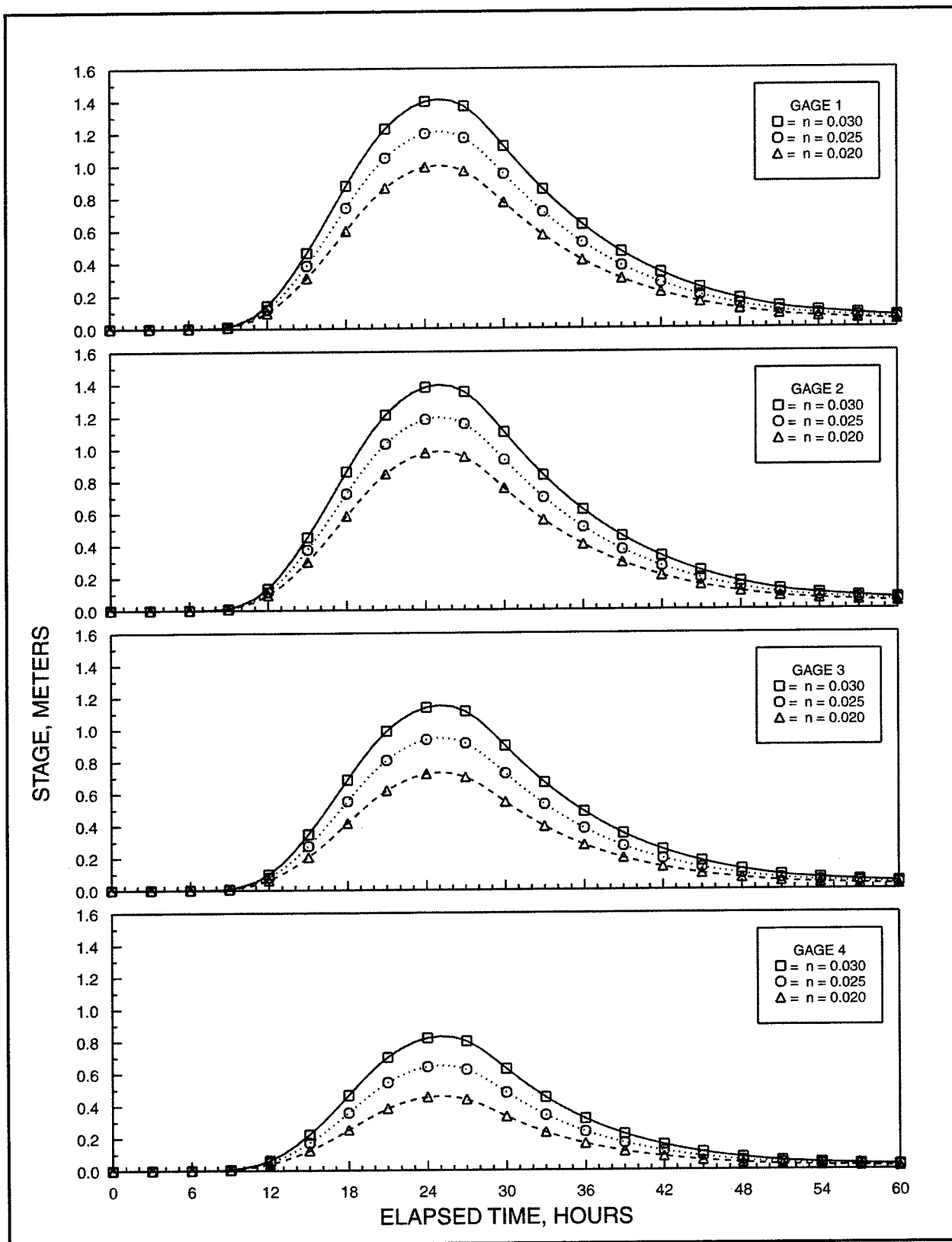


Figure 23. Effect of roughness on stage hydrograph

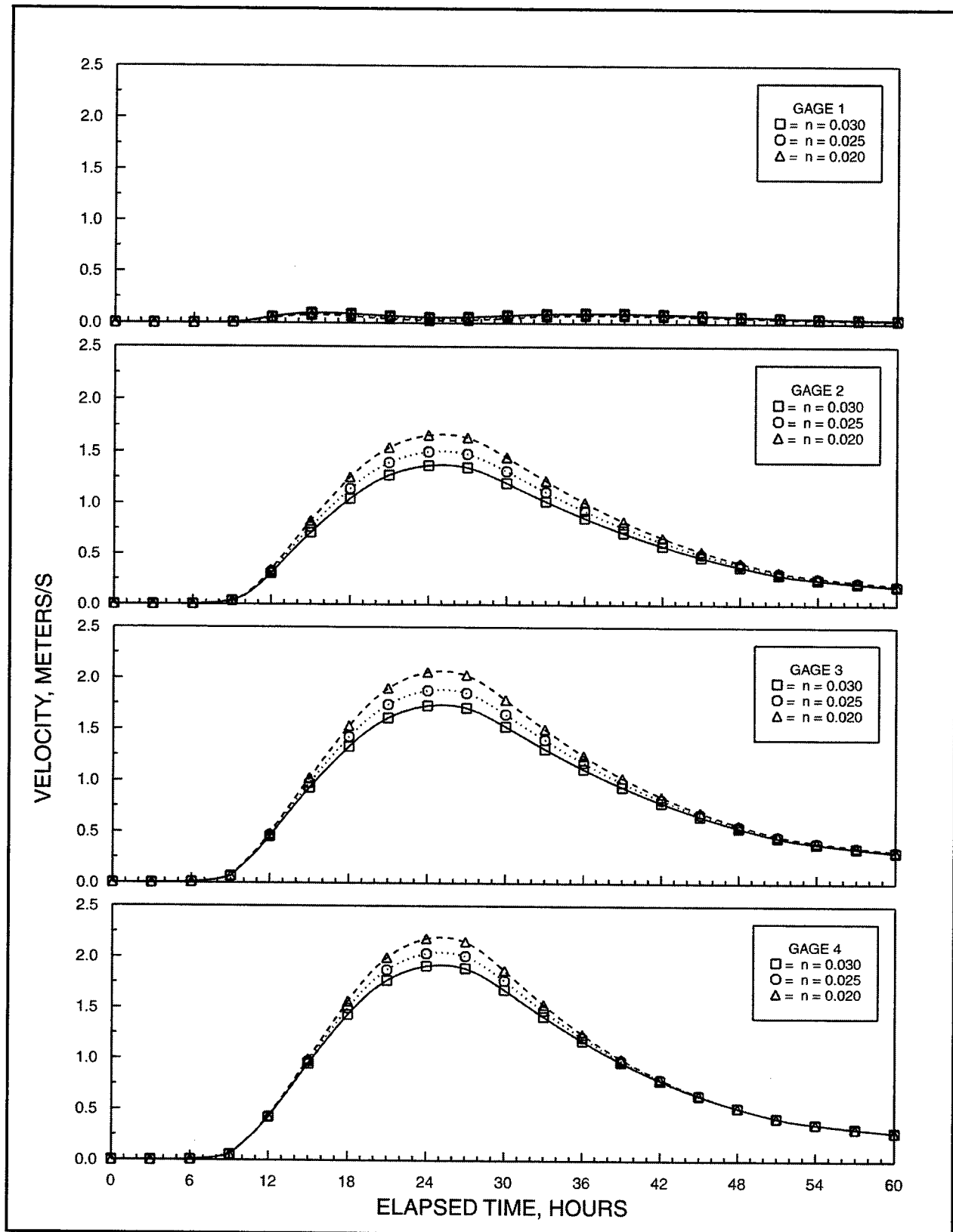


Figure 24. Effect of roughness on current speed

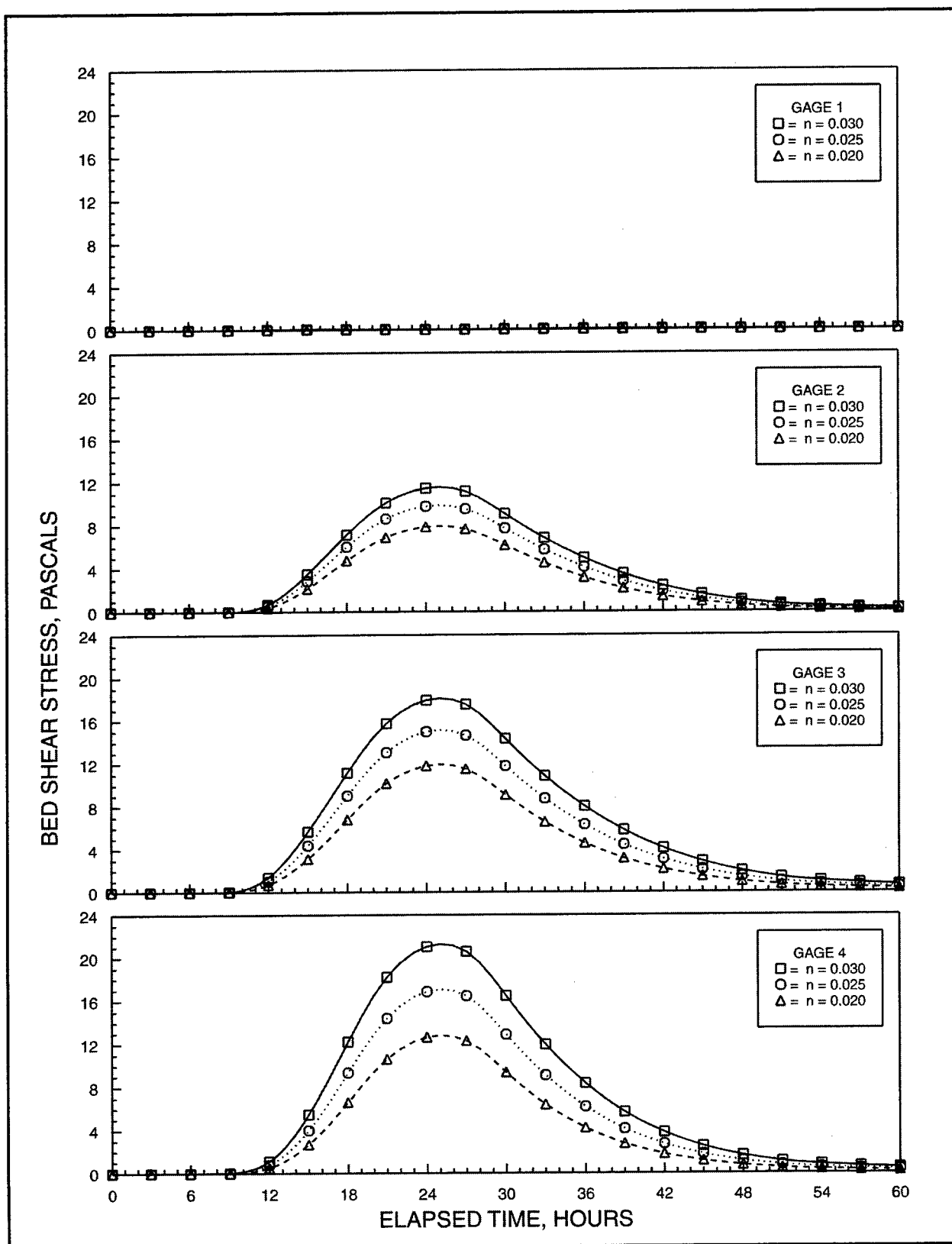


Figure 25. Effect of roughness on bed shear stress

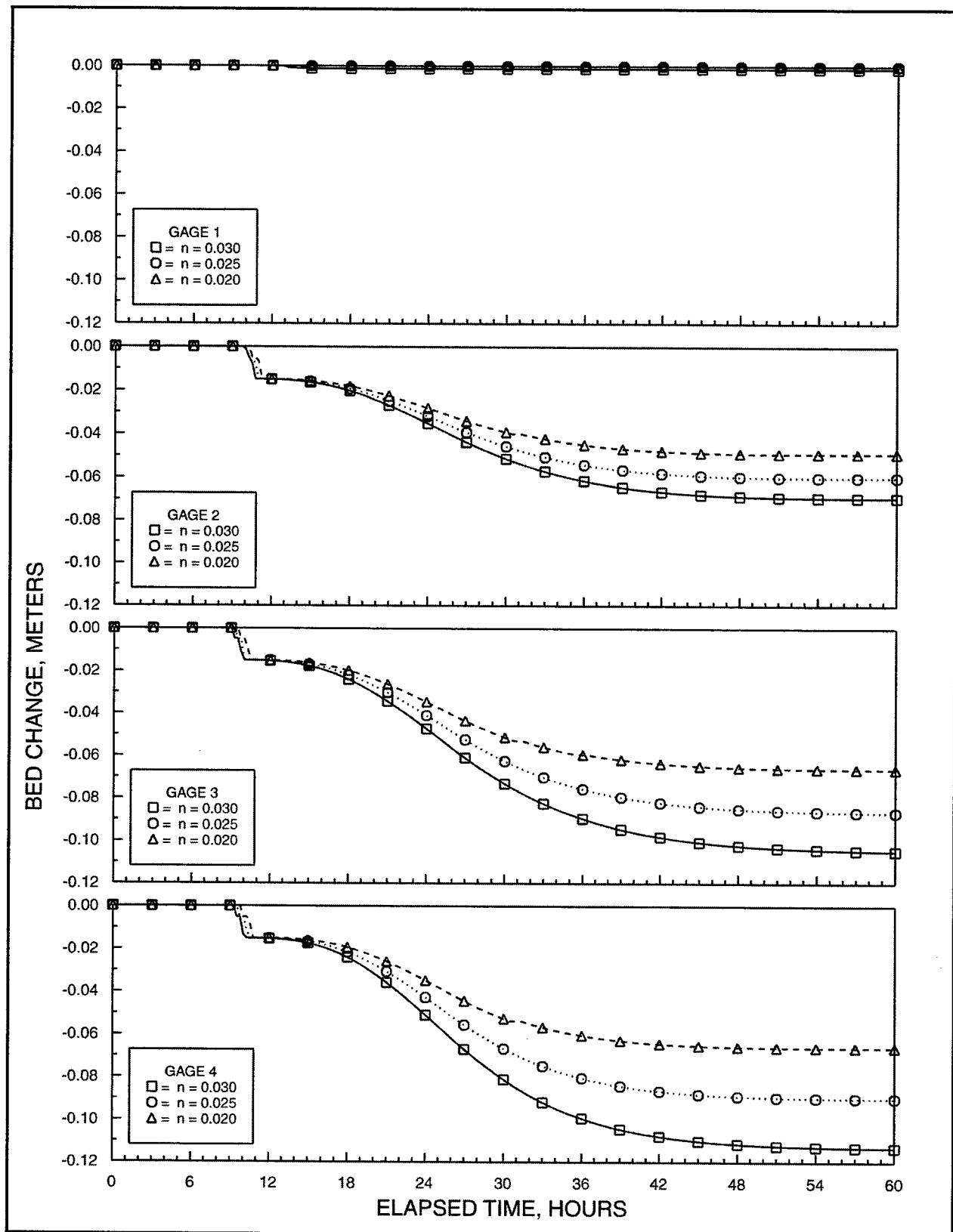


Figure 26. Effect of roughness on bed change

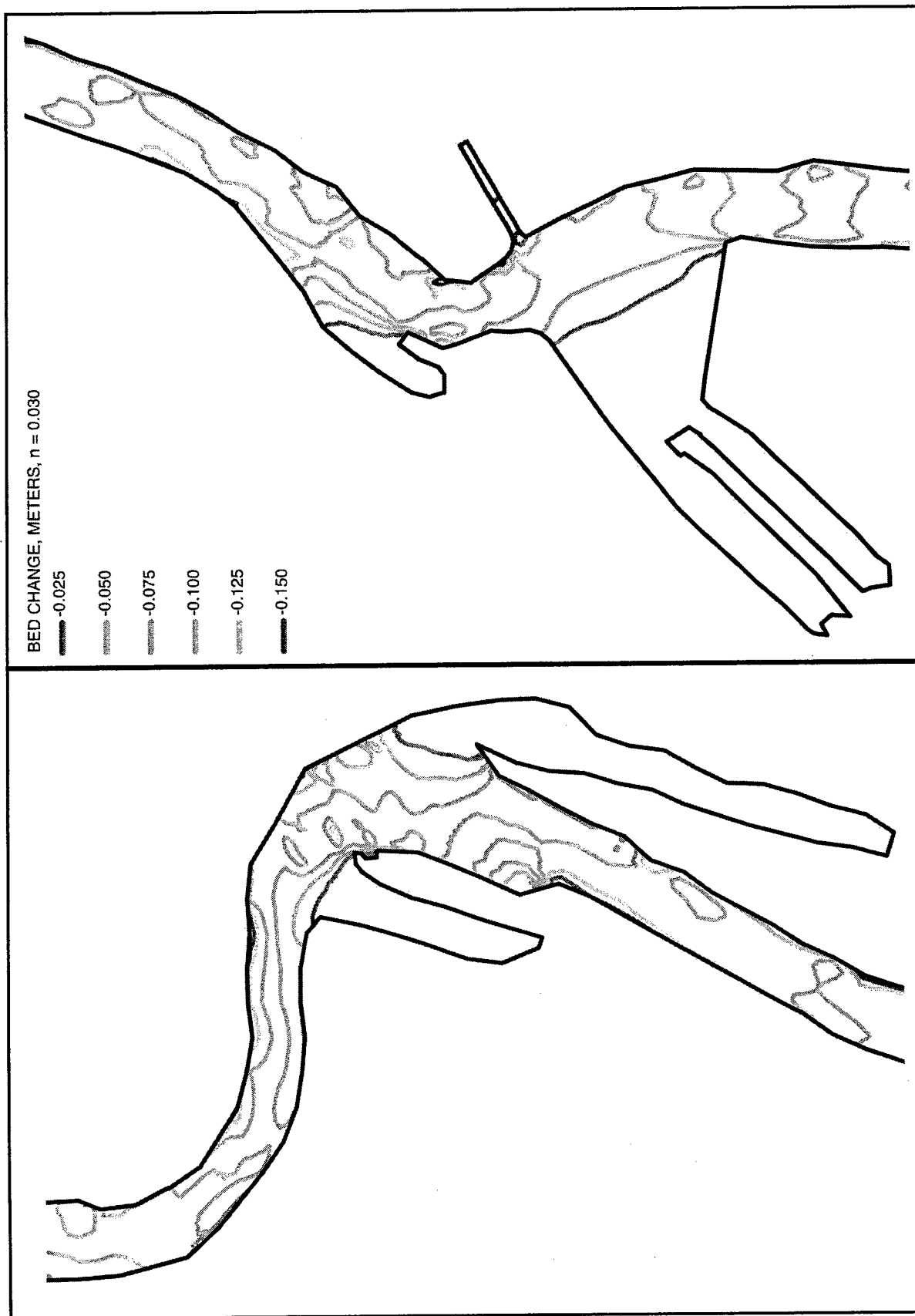


Figure 27. Accumulated scour for 20-percent increase in roughness

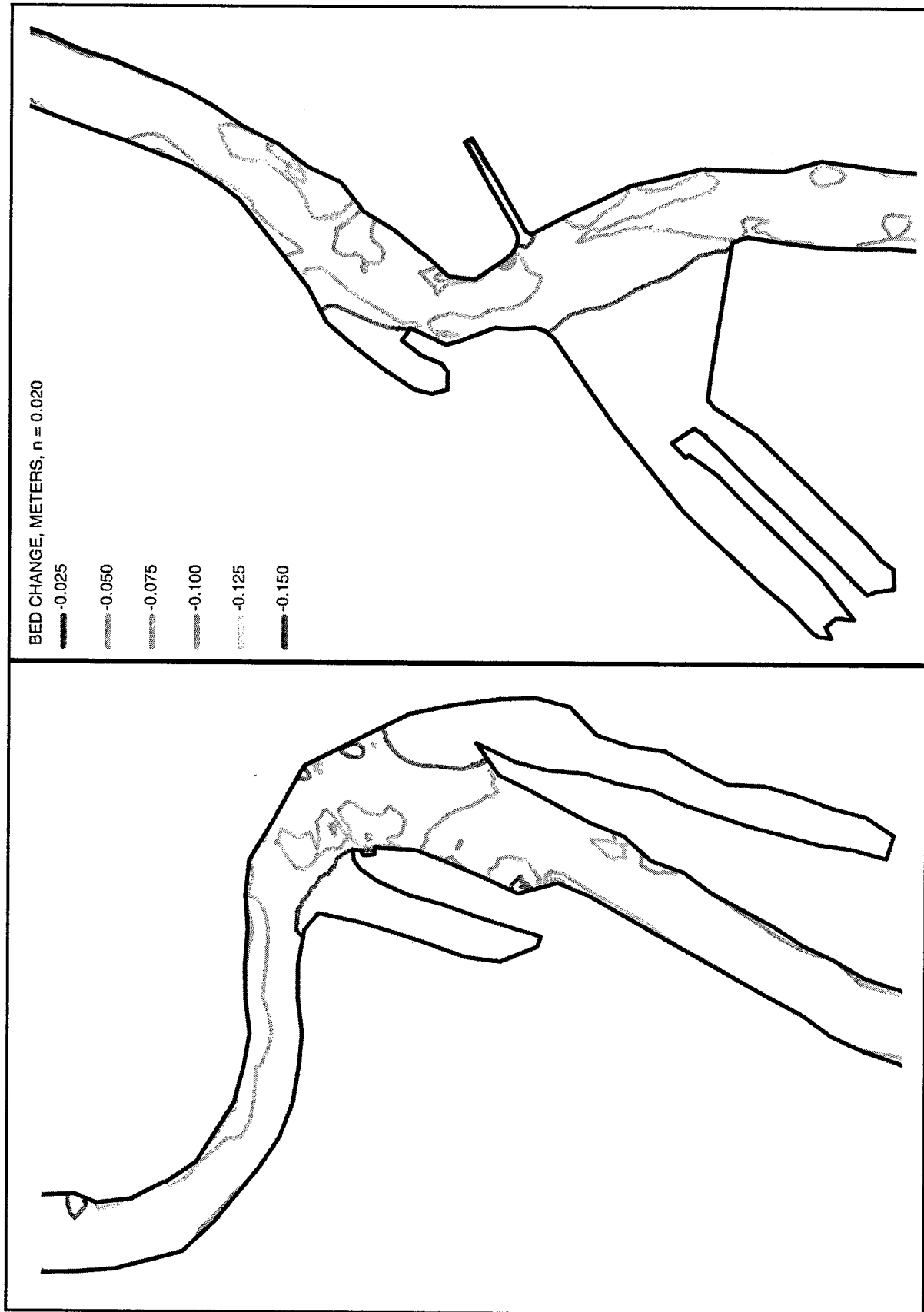


Figure 28. Accumulated scour for 20-percent decrease in roughness

upstream of the upper turning basin, which would have prevented successful completion of some simulation scenarios.

The effect of the turbulent exchange coefficient is most pronounced in areas outside the primary flow field. For example, the strength of circulation within the left side of the upper turning basin could be significantly altered by changing the coefficient value. Thus, the value would be significant if the model was being used to determine the amount of deposition in the turning basin. Its effect on the computed distribution of erosion is relatively small in the context of these flood-event simulations.

Erosion rate constant

Two erosion rate constants for model Layer 3 were tested: 1.6×10^{-5} and 1.6×10^{-4} kg/m²/sec. The higher value of the erosion rate constant represents the upper limit measured on Ashtabula River sediments (Teeter et al., in preparation) and represents a probable worst case estimate for this bed material. The lower value may be more representative of spring melt conditions, when temperatures in the Ashtabula River are lower than those at which the sediment erosion laboratory experiments were conducted. (Low-temperature effects have not been determined for Ashtabula River sediments, but have been determined for other similar sediments.) The best estimate of the erosion rate constant from the laboratory experiments was 1.2×10^{-4} kg/m²/sec or about 72 percent of the worst case value. Higher values of the erosion rate constant have been measured on other material (Lee and Mehta 1994). However, these other sediments have distinctive physical characteristics that account for the difference.

The cumulative bed change contours for an erosion rate constant of 1.6×10^{-4} kg/m²/sec are shown in Figure 29. The net effect of this change is to increase the depth of scour in Layer 3 by the same ratio as the erosion rate constant at those nodes where the shear stress exceeded the threshold for erosion. Upstream of the upper turning basin, erosion ranged from 50 to 90 cm. In the upper turning basin, erosion ranged from near zero in the left side of the basin to 30 to 60 cm in the right side of the basin. Immediately downstream of the basin in the vicinity of the railroad bridge, erosion ranged from 40 to 80 cm with small areas of erosion up to 130 cm along the right bank. In the reach downstream to the lower turning basin, erosion was typically in the range of 50 to 80 cm. Downstream of the lower turning basin to the 5th Street Bridge, erosion was typically in the 40- to 70-cm range. Using the higher erosion rate constant increased the total volume of erosion by about a factor of 6.

An estimate of the volume of PCB-contaminated sediments removed by scour upstream of the 5th Street Bridge as depicted in Figure 29 and the resulting surface-area-weighted PCB concentration at the exposed surface was developed using the GMS. First, the subsurface distribution and volume of the PCB plume within the channel bed sediments were determined

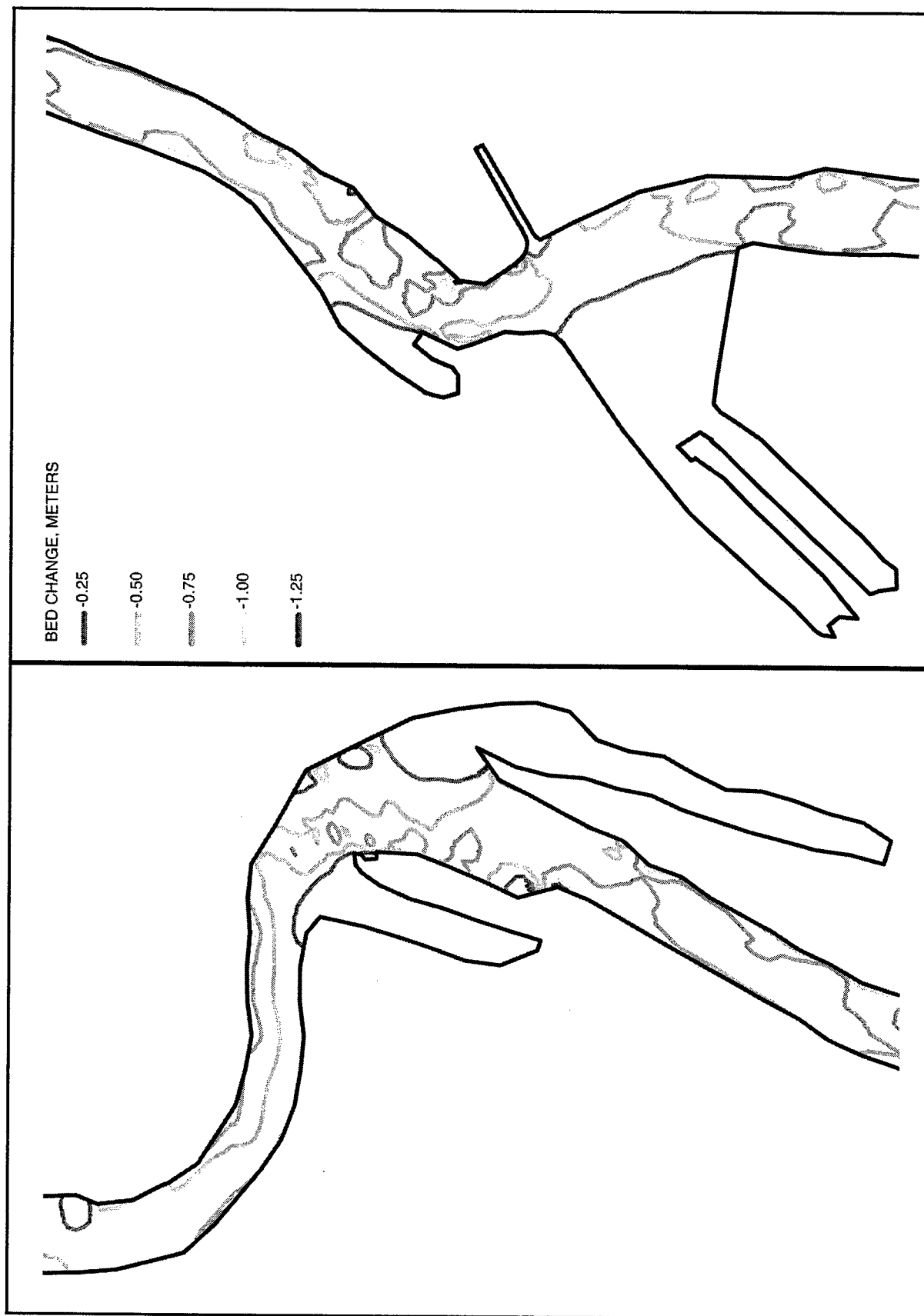


Figure 29. Maximum depth of scour for an order of magnitude increase in erosion rate constant

from sediment samples collected in 1990 and 1995.¹ Then, the post-event bed surface computed by the sedimentation model was imported into the GMS and used to determine the portion of the plume removed by scour.² The results from the GMS study are summarized in Table 3.

Table 3 Summary of GMS Study Results			
PCB Concentration ppm	Volume Removed by Scour m³	Surface-Area- Weighted PCB Concentration ppm	Exposed Surface Area 1,000 m²
Less than 0.5	33,600	0.09	71.4
0.5-1	3,500	0.03	7.5
1-5	12,000	0.52	33.8
5-10	8,800	1.07	27.7
10-20	12,500	2.14	27.7
20-30	3,900	1.92	14.9
30-40	4,000	1.14	6.3
40-50	1,600	0.42	1.8
Greater than 50	1,800	0.98	2.6
Totals	81,700	8.31	193.7

Changing the erosion rate constant has no impact on the computed hydrodynamics. However, the computed increase in depth using the higher value of the erosion rate constant was sufficient to produce a significant reduction in water surface slope and velocity during the simulation. To estimate the potential reduction in scour resulting from this increase in channel capacity, the computed erosion was subtracted from the initial bed surface to create a final bed surface that was used as the initial bed surface for an additional simulation of the 100-year return period flood event. The computed erosion from the additional simulation was generally 0 to 30 cm less than the amount of erosion computed during the initial simulation. Upstream of the upper turning basin, the differences were -10 to -30 cm. In the upper turning basin, the differences ranged from near zero in the left side of the basin to less than -10 cm in the right side of the basin. Immediately downstream of the basin in the vicinity of the railroad bridge, the typical difference ranged from -10 to -30 cm with small initially shallow areas along the right bank, corresponding to areas of relatively high erosion in the original simulation, where the difference

¹ Draft CEWES-HH-G Memorandum for: Commander, Buffalo District, regarding "Ashtabula River Contaminant Estimates" dated 29 April 1995.

² Draft CEWES-CH-G Memorandum for: Commander, Buffalo District, regarding "Data Report on Ashtabula River Contaminant Estimates" dated 23 January 1997.

approached -60 cm. In the reach downstream to the lower turning basin, the difference was typically in the range of -10 to -40 cm with differences being greatest at the downstream end of the reach. Downstream of the lower turning basin to the 5th Street Bridge, the typical difference ranged from -5 to -20 cm. Because the increase in channel capacity because of scour develops over the course of the flood event, the expected reduction in erosion would be about half of the differences generated using this procedure. Thus, the original estimate of erosion overstated the expected values by 10 to 20 percent upstream of the upper turning basin, by less than 10 percent in the upper turning basin, by 5 to 15 percent immediately downstream of the basin, by 10 to 25 percent in the reach downstream to the lower turning basin, and by 10 to 15 percent downstream to the 5th Street Bridge. For scenarios based on higher Lake Erie stages, this effect would be smaller because the computed erosion represents a smaller fraction of the water depth.

Qualitative Deposition

Although deposition of bed sediments was not modeled during this study, the hydraulic model results can be used to identify locations where significant deposition is likely to occur. The fine-grained bed material scoured during the flood event will not redeposit unless the bed shear stress is less than the critical shear stress for deposition. This value has not been determined for the bed sediments in the Ashtabula River; however, values in the range of 0.06 to 0.15 Pa are typical for fine sediments. A value at the lower end of this range is expected for the Ashtabula River sediments because laboratory measurements showed that the surficial sediment deposits will erode when subjected to bed shear stress in excess of 0.06 Pa. The areas of potential deposition for a critical value of 0.06 Pa are identified in Figure 30, a contour map of the simulation time in hours after the peak of the 100-year return period flood, a 35-hr period, during which computed bed shear stresses are less than 0.06 Pa. Areas outside of the 35-hr contour may experience deposition throughout the flood event, while areas inside the zero-hour contour are not expected to experience deposition of fine sediments until bed shear stress falls below the values computed at the end of the simulation period. Computed bed shear stresses are near zero throughout the simulated flood event in slack-water areas such as the lower turning basin and throughout Ashtabula Harbor except for the immediate vicinity of the mouth of the Ashtabula River. Deposition can be expected in the left side of the upper turning basin and in the entrance to the lower turning basin and other slack-water areas adjacent to the channel. Deposition rates are dependent on both the suspended-sediment concentration and the fall velocity of the sediment particles. Concentrations will be highest in the channel and increase in the downstream direction as eroded sediments enter the water column. Therefore, deposition rates in slack-water areas generally will be higher adjacent to the channel, and both concentrations and rates will decrease with distance from the channel. The remaining sediments will be flushed into the Harbor and Lake Erie. Most areas subject to scour will not experience deposition during the flood event. As the flood recedes, bed shear stress levels will fall below the deposition threshold in the commercial navigation

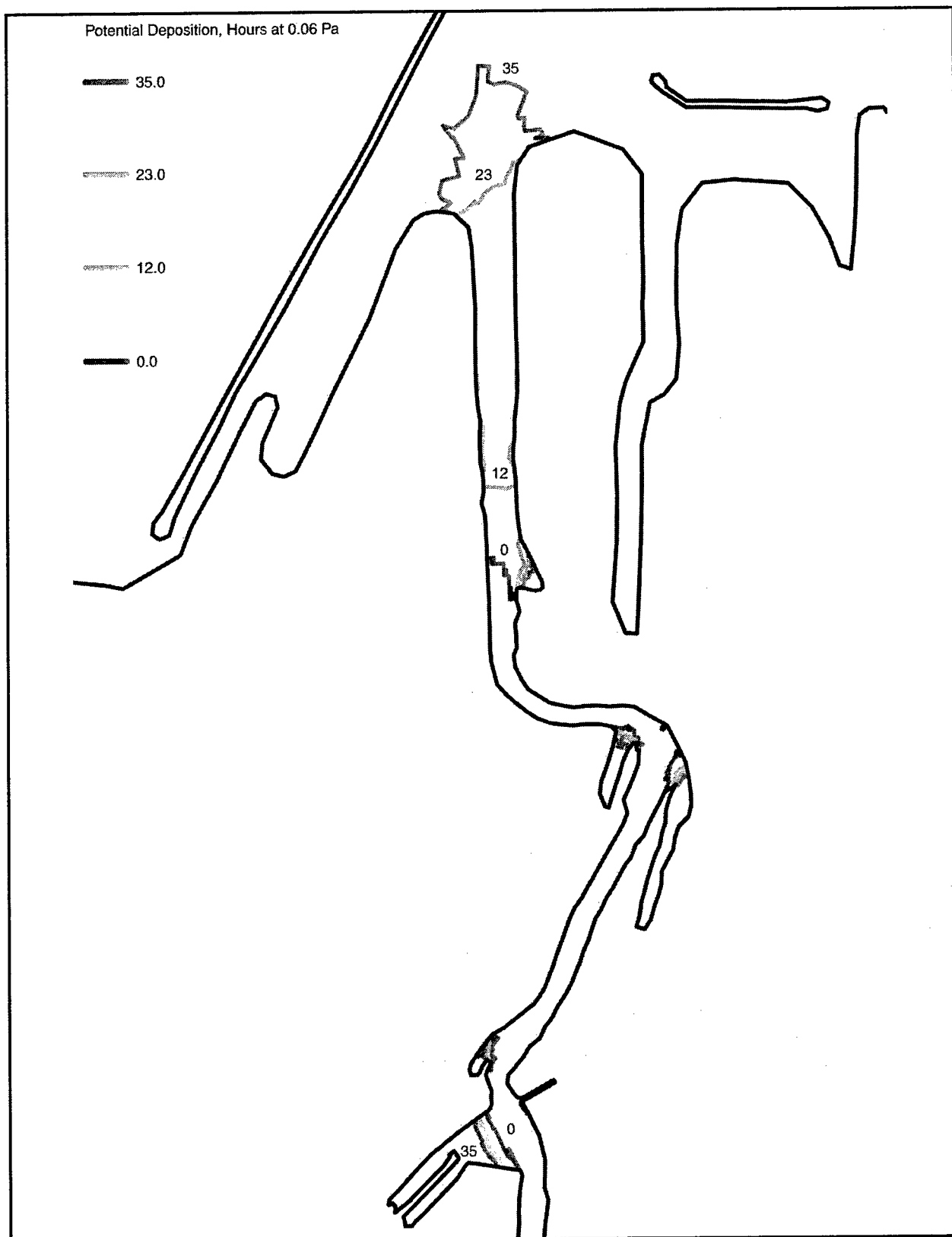


Figure 30. Hours of potential deposition after flood peak for a critical shear stress of 0.06 Pa

channel and then, assuming additional reductions in flow and bed shear stresses after the simulation period, throughout the system. As shown in Figure 30, deposition is expected to begin in portions of the commercial navigation channel during the last day of the simulated flood event.

Because the most heavily contaminated bed material removed by the computed erosion is located in the upper turning basin and immediately downstream in the vicinity of the railroad bridge, slack-water deposits in the upper turning basin and in the shallow area on the left bank downstream of the bridge are likely to contain greater concentrations of PCBs than deposits further downstream. The actual concentrations will be significantly lower than in existing bed material as a result of physical and chemical transformations occurring during the erosion, transport, and deposition processes and dilution with cleaner sediments.

The magnitude of deposition will be dependent not only on the volume of material eroded from the bed within the study area but also on the grain-size distribution and rate of sediment inflow from the Ashtabula River and Fields Brook and Strong Brook. Currents at the peak of the simulated flood event are sufficient to transport coarse-grained sediments (sand and gravel) into the study area. Significant deposition of sand could occur downstream to the mouth of the river, while significant deposits of gravel are likely to be restricted to the upper turning basin and the channel upstream of the basin. The total volume of post-flood sediment deposits may be larger than the volume of erosion. The actual distribution of fine-grained sediment deposits in the Harbor will be determined primarily by wind- and lake-induced currents. In the absence of significant energy from these sources, the heaviest deposits can be expected in the vicinity of the mouth of the Ashtabula River.

4 Discussion of Results

Modeling of sedimentation processes in natural systems is inherently challenging and especially so for extreme events where scientific observation is limited both by infrequent occurrence and by extreme (and usually hazardous) field conditions. The accuracy of model estimates of scour distribution and magnitude are limited primarily by uncertainties in the data used within the model to describe the natural system.

The most significant model parameter identified in this study was the erosion rate constant. The worst case estimate of this constant was approximately one-third larger than the mean or best estimate; thus, the worst case estimate, represented by Figure 29, overestimates the expected erosion by approximately one-third. The laboratory experiments performed to determine the erosion rate constant used devices capable of imposing shear stresses up to 2.3 Pa. Computed bed shear stresses during the 100-year return period flood simulation are an order of magnitude higher. The absence of experimental data at this higher shear stress level is the most significant uncertainty associated with the computed scour. The primary concern is that the actual erosion rate may be higher than estimated at the higher shear stress levels. Although the laboratory devices used to determine the erosion rate constant represented the best available technology at the time of the study, experimental devices are under development that would permit in situ determinations of erosion rates at 10 Pa or higher.

The most significant parameter in the hydrodynamic model computations was the estimated roughness coefficient. Varying this coefficient by ± 20 percent produced differences of -20 to +23 percent in the computed erosion. In the authors' opinion, the selected value of 0.025 is reasonable for a relatively wide channel with a smooth bed composed of fine-grained sediments, and the range of values tested encompasses the likely natural variations in roughness. Determination of the actual roughness coefficient would require measurements during an actual flood event.

Scour was estimated for three different 100-year return period flood-event scenarios, each corresponding to a different Lake Erie stage. Lake Erie stages can be considered to be independent of the probability of experiencing an event equal to or exceeding the 100-year return period flood except for seasonal variations in the stage and flood-probability distributions. As compared with the low water datum scenario (Case 1), the average stage scenario (Case 2) produced approximately 30 percent less

erosion, and the erosion was distributed more evenly over the channel. A qualitative understanding of the uncertainty present in the model results can be obtained by considering the following scenarios. If the mean estimate of the erosion rate constant were substituted for the worst case estimate in the average stage scenario, the expected erosion (ignoring differences in distribution) would be about one-half of the amount shown in Figure 29. Higher stages would result in even less erosion. Alternately, for a scenario combining the worst case estimate of the erosion rate constant with a 20-percent increase in the estimated roughness coefficient with the Lake Erie stage set at the low water datum, the expected erosion would be 20 to 25 percent greater than the amount shown in Figure 29.

5 Summary and Conclusion

These numerical model simulations were conducted using the bathymetry observed in 1995. Both natural and man-made alterations to this bathymetry could modify the magnitude and distribution of scour. For example, dredging the navigation channel can be expected to reduce the total volume of scour experienced during a flood event but could also alter the distribution of scour, possibly increasing the depth of scour at some locations within the navigation channel.

The field data that have been collected to date are essentially of a low-flow nature. In the absence of field data characterizing higher flow conditions, selection of values for some model coefficients was by necessity based on the professional judgment of the modeling team. Reliable estimates of the accuracy of the hydrodynamic and sedimentation model computations will require the collection of additional field data. Unfortunately, given the short duration of flood events in this system and the infrequency of events that produce significant erosion, an expensive, long-term commitment to automated monitoring of the system would be required to produce the required data. However, in the opinion of the modeling team, the results of the model simulations presented herein are reasonable and consistent with the expected behavior of this system.

The 100-year return period flood event does not represent the largest flood event that can reasonably be expected to occur in the future. Larger events can be expected to produce greater depths and different distributions of scour. This study does not rule out the possibility that a larger event could produce bed shear stresses capable of causing mechanical failure of the bed material producing significantly greater scour.

Smaller, more frequent flood events can be expected to produce smaller depths and different distributions of scour. Unless flood events occur in rapid succession, the scour will not be cumulative because significant deposition is likely after each flood event. However, each event will result in some downstream transport, mixing, and redistribution of contaminated sediments causing an increase in the aerial distribution of contamination.

The maximum computed depth of scour for the 100-year return period flood event with the Lake Erie stage held at the low water datum was generally less than 1 m throughout the area of interest (with limited areas of scour up to 1.3 m) and less than 0.6 m in the upper turning basin as displayed in Figure 29. The computed depth of scour was significantly

smaller for higher (and more probable) Lake Erie stages. Likewise, the same flood event coincident with a lower Lake Erie stage would be expected to produce greater scour.

Bed sediment characteristics are the most significant factor in determining the expected depth of scour. If the actual erosion rate constant for the sediments is less than the higher estimate of 1.6×10^{-4} kg/m²/sec, then the depth of scour will be proportionally smaller than the amount shown in Figure 29.

The values of the erosion rate constant used in these simulations were developed from laboratory measurements of erosion of Ashtabula River bed material samples. However, the peak computed bed shear stresses for the 100-year return period flood event exceed the maximum bed shear stress applied in the laboratory by an order of magnitude. As shown in Figure 16, the use of a single erosion rate constant implies that the erosion rate increases linearly with excess bed shear stress. The possibility of a greater than linear increase in erosion rate at shear stress levels greatly exceeding those measured in the laboratory cannot be discounted. In the absence of laboratory or field measurements at high bed shear stress levels, the higher estimate of the erosion rate constant should be considered to be a reasonable worst case estimate of the potential maximum depth of scour.

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Appendix A

Annotated Bibliography of Numerical Modeling

Apicella, Guy, Norris, Robert, Newton, Johanna, Ewald, Walter, Fordran, Angelika. (1994). "East River modeling of water quality for multiple-project assessments." *Proceedings of the 3rd International Conference on Estuarine and Coastal Modeling III*, Oak Brook, IL. American Society of Civil Engineers, New York, 235-248.

The East River Model (ERM), which employs the RMA-2V hydrodynamic and RMA-4 water quality modeling code, was used by Lawler, Matusky & Skelly Engineers to assess water quality impacts in conjunction with a number of programs administered by the New York City Department of Environmental Protection. The two modeling applications described in this paper relate to (1) combined sewer overflow (CSO) effects on dissolved oxygen (DO) and total coliform concentrations, and (2) water pollution control plant (WPCP) effluent dilution as related to whole effluent toxicity (WET) criteria. Two dye surveys at each of the city's six WPCPs revealed that the effluent is well mixed vertically at relatively short distances from the outfall. The ERM was used to simulate the effect of the city's 239 CSO outfalls on DO and total coliform within the East River system and thereby develop a plan for CSO abatement.

Athow, R. F., Berger, R. C., Heltzel, S. B., and Trawle, M. J. (1986). "Predicting maintenance dredging requirements: a case study, Thimble Shoal and Elizabeth River Channels, Norfolk, Virginia, USA." *XIth World Dredging Congress*, Brighton, United Kingdom, March 4-7, 1986. J. H. Volbeda, V. L. van Dam, N. Oosterbaan, ed., Central Dredging Association, Delft, The Netherlands, Section A, Part A2, Paper a, 19-33.

Describes how the TABS-2 numerical modelling system was used to study proposed channel and anchorage improvements for Norfolk Harbour. The noncohesive mode of the numerical sediment model (STUDH) was used for the Thimble Shoal Study and the cohesive mode applied to the Elizabeth River study. In both studies the finite element hydrodynamic model RMA-2V was used. Describes procedures used, noting determination of shoaling rates.

Athow, Robert F., Jr., Trawle, Michael J., and Richards, David R. (1987). "Numerical evaluation of training structures." *Hydraulic engineering: Proceedings of the 1987 National Conference*, Williamsburg, VA, August 3-7, 1987. American Society of Civil Engineers, New York, 345-350.

A technique to evaluate estuarine training structure performance in reducing localized maintenance dredging requirements using the US Army Corps of Engineers TABS-2 numerical modeling system is presented. An application of the two-dimensional, vertically averaged numerical model is demonstrated with emphasis on high-resolution computational grids and sediment transport. A short reach of the Columbia River estuary is simulated in the numerical model. The modeled reach includes four spur dikes constructed to reduce shoaling in the adjacent navigation channel. Using the model, shoaling rates are predicted in the navigation channel with the dikes in place and then with the dikes removed.

Berger, R. C. Jr. (1990). "Channel maintenance by training structures: Guidance for numerical model mesh development," Technical Report HL-90-13, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Training structures used to control channel currents and sedimentation, which in the past were designed by rules of thumb, are now frequently the subject of numerical model investigations. The precision and stability of numerical models representing the shallow-water equations and transport generally are strongly influenced by the nature of the computational mesh upon which the calculations take place. This condition is amplified by the presence of man-made structures in the flow. It is therefore imperative that mesh development in the vicinity of these structures be guided so that accurate and reliable shoaling predictions result.

This report uses a series of simple linear model equations applied in a finite element framework to develop guidance for the minimum mesh expansion rate, orientation, skewness, oscillation suppression, and bathymetric effects. While this effort was aimed at the TABS-2 modeling system, the findings are generally applicable to other finite element and finite difference models. Appendix A discusses the elimination of oscillations in the TABS-2 program.

Berger, R. C. (1990). "Mass conservation in the RMA2V code." *Hydraulic Engineering: Proceedings of the 1990 National Conference*, San Diego, CA, July 30-31, 1990. American Society of Civil Engineers, Boston Society of Civil Engineers Section, Boston, MA, 2, 873-878.

This paper discusses the RMA2V hydrodynamic code with a particular interest in mass conservation problems. These originate from at least two sources. One of which is the slip flow boundary specification in which the boundary slopes are not continuous and the second is due to the formulation itself. The severity of these problems is estimated and recommendations made to improve the model behavior.

Berger, R. C., McAdory, R. T., Martin, W. D., and Schmidt, J. H. (1995). "Houston-Galveston Navigation Channels, Texas Project; Report 3: Three-dimensional hydrodynamic model verification," Technical Report HL-92-7, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

This report describes the verification results of the three-dimensional (3-D) hydrodynamic model used to evaluate tides, current velocities, and salinities in Galveston Bay, Texas. This is the third in a series of reports concerning the Houston-Galveston Navigation Channels. The goal of these reports is to determine the effect of the proposed channel deepening and widening upon tides, currents, salinities, and navigation. Report 1 describes the field data collection and results, Report 2 presents the two-dimensional numerical modeling of hydrodynamics for a navigation study, Report 3 presents the verification description for the 3-D model, and Report 4 details the results of tests of the 3-D model.

This report first describes the 3-D model program, RMA10-WES, which is a finite element code using mixed quadratic and linear Lagrange polynomials. The remainder of the report reveals the

demonstration of the model applicability through the verification procedure. This procedure of adjustment and verification was first a comparison to a short series of data with a series of adjustments in bed roughness. Then the model was run with no adjustment over a period of roughly 6 months in comparison to field data from 19 July 1990 to 15 January 1991. This period includes the time following a major flood in the Galveston Bay system for which the model reproduces the timing and magnitude of the salinity rebound very well. Comparisons of model performance are drawn qualitatively between the model and description of the Bay in the literature, and also quantitatively with the field data recorded for this study.

Berger, R. C., Jr., Heltzel, Samuel B., Athow, Robert F., Jr., Richards, David R., Trawle, Michael J. (1985), "Norfolk Harbor and channels deepening study; Report 2, Sedimentation investigation; Chesapeake Bay hydraulic model investigation," Technical Report HL-83-13, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

This report presents the sedimentation findings from combined physical and numerical model tests (hybrid modeling) of deepening the approach channels to Norfolk and Newport News, VA. Because of the varying nature of shoaled material along the project navigation channel, the tests included two separate numerical sediment transport models, which were referred to as the Thimble Shoal model and the Elizabeth River model. The sediment along the Thimble Shoal portion of the navigation channel consists predominantly of noncohesive material while the sediment along the Elizabeth River portion of the navigation project consists primarily of clays and silts. Sedimentation in a third portion of the overall project, referred to as the Atlantic Ocean Channel, was evaluated analytically without using a numerical sediment transport model.

Based on sedimentation results from the Elizabeth River numerical model, the increase in shoaling caused by channel deepening as proposed will be 23 percent. The distribution of shoaled material will not be significantly altered, other than a slight increase in skewness toward the downstream end.

Based on sedimentation results from the Thimble Shoal numerical model, the increase in shoaling caused by channel deepening as proposed will be about 20 percent. The distribution of shoaled material will be slightly altered in that both the upper and lower channel shoaling peaks which presently exist will tend to migrate even more toward the ends of the dredged channel.

Based on the analytic analysis, the estimate of shoaling for the new Atlantic Ocean Channel is about 200,000 cu yd annually.

Berger, R. C., McAdory, Robert T., Schmidt, Joseph H., Martin, William D., and Hauck, Larry H. (1995). "Houston-Galveston Navigation Channels, Texas Project; Report 4, Three-dimensional numerical modeling of hydrodynamics and salinity," Technical Report HL-92-7, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

This report describes the testing program conducted to evaluate the impact of enlargement of the Houston-Galveston Navigation Channel on

the salinity and hydrodynamic fields of tidally influenced Galveston Bay. The present channel nominal dimensions are 40 ft deep at mean low water (mlw) and 400 ft wide. The proposed enlargements tested are for a channel 45 ft deep at mlw and 530 ft wide (Phase I) and 50 ft deep and 600 ft wide (Phase II). Current plans do not include the Phase II enlargement. Salinity fields for these channel configurations and the existing channel dimensions are compared. In a separate study the results from these simulations were used to drive an ecosystem model to predict oyster production.

Testing conditions included tidal conditions and winds for the year 1984. The freshwater inflows (developed outside this study) were tested for low-, medium-, and high-flow years. Additionally, since water demand in the future is expected to modify freshwater distribution and quantities, future distributions for the test year 1999 (Wallisville Dam in place), 2024, and

The code used (RMA10-WES) is a Galerkin-based finite element solution to simulate three-dimensional (3-D) unsteady open-channel flow. The code represents 3-D hydrodynamics using conservation of fluid mass, horizontal momentum, and salinity/temperature transport equations subject to the hydrostatic assumption.

Results of these tests showed that the largest increases in salinity were in low-salinity areas, including the upper west side of the bay across the channel from Atkinson Island, and the upper bay channel. Trinity Bay showed a small salinity increase. South of midbay the salinity increases were generally less than 1 ppt. Some locations in the south bay near the navigation channel occasionally showed a decrease in salinity for the deeper channel configurations. These decreases occurred during the period of rebound in salinity after the high inflow period of late spring.

The deepened channels showed increased salinity stratification. The stratification increased with channel project depths and with freshwater in flow in the Buffalo Bayou/San Jacinto River Basin.

The future hydrologic scenarios result in more freshwater inflow to Galveston Bay through Buffalo Bayou and San Jacinto River. The deepened channels typically resulted in less significant salinity increases in the scenarios than for the present hydrologic year (1990). These future scenarios redistribute some of the freshwater inflow from the Trinity River and reintroduce it through Buffalo Bayou and San Jacinto River. The model indicates a corresponding increase in salinity in Trinity Bay and decrease in the eastern upper bay salinity.

Cheramie, Kirk. (1995). "Hydrologic modeling of fresh water resources." *Coastal Zone: Proceedings of the Symposium on Coastal and Ocean management*, Tampa, FL. American Society of Civil Engineers, New York, 294-295.

This paper specifically identifies the TABS-MD model designed by the U.S. Army Corps of Engineers, Waterways Experiment Station as an effective management tool for efficiently supplying raw fresh water resources to coastal communities. Through the use of the TABS-MD computer model, the Bayou Lafourche Fresh Water District, a state

political sub-district, is able to adequately supply fresh water to eight percent of the population of Louisiana. The model incorporates boundary conditions such as tidal range, stage, velocity and constituent concentrations within Bayou Lafourche, a 110 mile fresh water channel between the Mississippi River and the Gulf of Mexico. By setting boundary conditions and executing the model, management can decide upon the quantity of fresh water that must be pumped into Bayou Lafourche at its headwaters in order to regulate salinity concentrations at fresh water intakes at its southern most locations. By accurately determining the amount of fresh water required to offset saltwater intrusion, the expenditure of public tax dollars on electricity and fuel for fresh water pumps are better estimated, yielding savings to the public while at the same time insuring an adequate fresh water supply.

Coleman, Wesley E., Jr. (1992). "Chesapeake bay field modeling and monitoring projects." *Coastal engineering practice '92*, Long Beach, CA, March 9-11, 1992. American Society of Civil Engineerings, New York, 221-233.

'Traditional' erosion control measures often do not meet the Corps of Engineers' requirement for economic justification. The costs of these measures are much greater than the benefits provided. The costs are also prohibitive to property owners seeking shoreline protection. The Chesapeake Bay Shoreline Erosion Study has provided information for designing offshore breakwaters more cost-effectively to encourage implementation of these measures in the interest of Bay-wide improvement. Offshore breakwaters were installed at two locations in the Bay, and their performance was monitored.

Comes, Bradley M., Copeland, Ronald R., and Thomas, William A. (1989). "Red River Waterway, John H. Overton Lock and Dam; Report 5, Sedimentation in lock approaches; TABS-2 numerical model investigation," Technical Report HL-89-16, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

A two-dimensional numerical model, TABS-2, was used to predict fine sediment deposition in the lock approach channels upstream and downstream from the John H. Overton Lock and Dam on the Red River Waterway, Louisiana. The numerical model was used to evaluate the effects of various design changes on fine sediment deposition. These included changing the length and height of divider dikes, the number of openings on the ported guard wall, the invert elevation in the lock approach channel, and the location of spur dikes.

Copeland, Ronald R., and Thomas, William A. (1988). "Red River Waterway sedimentation study downstream from Lock and Dam No. 1; Numerical model investigation," Technical Report HL-88-15, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

The effect of recently constructed and proposed channel improvements on sedimentation in the Red River downstream from Lock and Dam No. 1 were investigated. A one-dimensional numerical model (HEC-6) was used to evaluate the effect of contraction works on dredging requirements in the navigation channel. A two-dimensional numerical model (TABS-2) was used to evaluate proposals to reduce deposition

in the downstream lock approach channel at Lock and Dam No. 1. Recommendations were made to reduce sediment problems in the study reach.

Copeland, Ronald R., Comes, Bradley M., and Thomas, William A. (1991). "Red River Waterway, Lock and Dam No. 3; Report 5, Sedimentation in lock approaches; TABS-2 numerical model investigation," Technical Report HL-91-10, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

A two-dimensional numerical model, TABS-2, was used to predict fine sediment deposition in the lock approach channels upstream and downstream from Lock and Dam No. 3 on the Red River Waterway, Louisiana. The numerical model was used to evaluate the effects of various design changes on fine sediment deposition. These included the cross-section shape in the upstream lock approach channel, the distance between the lock wall and the first spillway gate, the number of openings in the ported guard wall, and location of a berm in the upstream channel.

Copeland, Ronald R., Heath, Ronald E., and Thomas, William A. (1990). "Red River Waterway, Lock and Dam No. 4; Report 5, Sedimentation in lock approaches; TABS-2 numerical model investigation," Technical Report HL-90-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

A two-dimensional numerical model, TABS-2, was used to predict fine sediment deposition in the lock approach channels upstream and downstream from proposed Lock and Dam No. 4 on the Red River Waterway, Louisiana. The numerical model was used to evaluate alternative designs. Fine sediment deposition with the proposed design at Lock and Dam No. 4 was compared to fine sediment deposition at existing locks and dams downstream.

Copeland, Ronald R., Combs, Phil, and Little, Charles D. (1989). "Application of 2-D model to reduce sedimentation problems." *Sediment Transport Modeling: Proceedings of the International Symposium*, New Orleans, LA, August 14-18, 1989. American Society of Civil Engineers, New York, 124-129.

The Corps of Engineers opened Lock and Dam No. 1 on the Red River Waterway in 1984. During the first runoff season, excessive quantities of fine sediment deposited in both the upstream and downstream lock approach channels. Two-dimensional numerical model studies using the TABS-2 computer programs were conducted to determine remedial measures to significantly reduce hydraulic dredging, especially in the vicinity of the lock miter gates. This paper addresses the studies and evaluates the effectiveness of the construction measures.

Deering, Michael K. (1990). "Practical applications of 2-D hydrodynamic modeling." *Hydraulic Engineering: Proceedings of the 1990 National Conference*, San Diego, CA, July 30-31, 1990. American Society of Civil Engineers, Boston Society of Civil Engineers Section, Boston, MA, 2, 755-760.

Two-dimensional hydrodynamic modeling capability has greatly impacted the hydraulics community and significantly altered the approaches to design and analysis of open channel systems. Two-dimensional modeling has the potential for eliminating over simplified assumptions associated with one-dimensional modeling. In some cases it may negate the need for physical model studies. Five case studies that employed two-dimensional hydrodynamic methods are presented.

Demissie, Misganaw, Soong, David, and Bhowmik, Nani G. (1988). "Hydraulic study for the construction of artificial islands in Peoria Lake, Illinois." *Hydraulic engineering: Proceedings of the 1988 National Conference on Hydraulic Engineering*, Colorado Springs, CO, August 8-12, 1988. American Society of Civil Engineers, New York, 340-345.

Long-term sediment accumulation in the lake reduced the average depth of the lake from 8 feet in 1903 to 2.6 feet in 1985, which resulted in the deterioration of aquatic habitats and recreational areas in the lake. A detailed hydraulic analysis was needed to evaluate the feasibility creating islands in Peoria Lake. The major hydraulic considerations include determining the optimum locations for the islands in terms of minimizing the sedimentation rates around the islands. A hydraulic study was conducted to investigate the best locations for constructing islands in the lake. The study made use of the one-dimensional HEC-6 sediment transport model and the two-dimensional TABS-2 hydrodynamic model. Field data were also collected to establish existing lake-bottom profiles and velocity distributions at selected locations.

Evans, Robert A. (1992). "Lockwoods Folly numerical circulation study," Technical Report HL-92-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

The region around Lockwoods Folly River and Inlet, North Carolina, has experienced increased development in the past 50 years. In addition, the inlet has been changed by the addition of the Atlantic Intracoastal Waterway (AIWW). There have been concerns that the circulation is not sufficient to maintain good water quality. These concerns led the US Army Corps of Engineers to conduct an investigation to determine the effect of the AIWW on overall circulation patterns. The technical approach for this investigation was built upon the TABS-MD finite element modeling system. The two-dimensional model for hydrodynamics was first validated to limited prototype data, then used in conjunction with the transport model to predict the changes in tracer levels between the base condition and three plan conditions.

Fischenich, J. Craig. (1990). "Cumulative impacts analysis on a midwest fluvial system." *Hydraulic Engineering: Proceedings of the 1990 National Conference*, San Diego, CA, July 30-31, 1990. American Society of Civil Engineers, Boston Society of Civil Engineers Section, Boston, MA, 2, 802-807.

The US Army Corps of Engineers recently completed an analysis of the cumulative impacts of erosion control structures on the Platte River in Nebraska. This was done in response to concerns about the effects of bank stabilization activities upon threatened and endangered species that use the Platte River. Physical changes to the river generated by existing and proposed bank stabilization activities were evaluated to determine the environmental significance of various bank stabilization structures. HEC-6, a one-dimensional sediment transport model, was used to quantify cumulative impacts from bank stabilization activities for the entire river. TABS-2, a two-dimensional sediment transport model, was used to quantify local impacts from a variety of structures.

Ford, R. Glenn, Sobey, Rodney J., Shrestha, Parmeshwar L., Saviz, Camilla M., Orlob, Gerald T., King, Ian P. (1993). "San Francisco Bay and Delta oil spill fate studies. Part II: Oil spill simulation." *Proceedings, National Conference on Hydraulic Engineering*, San Francisco, CA. American Society of Civil Engineers, New York, 641-646.

Because of the presence of oil refineries and significant tanker and barge traffic in the bay and delta region, the possibility of a moderate or major spill in the area must be considered. We have constructed a general model that calculates a Lagrangian element solution for an oil spill in this region. Surface currents are simulated using output from the U.C. David RMA-2V model. We combine the surface current fields with real time sequences of wind speed and direction collected at eight sites in the bay and delta areas during 1990 and 1991 interpolated to form a smooth spatially varying wind field. A random diffusive component is added to simulate spreading. The magnitude of the diffusive component and the number of Lagrangian elements are adjusted to simulate spills of varying sizes. Characterization of intertidal substrates in this area is based on 1:24,000 scale digital maps and the National Wetlands Inventory. Oil particles are not permitted to cross exposed mud or marsh, or they are assumed to strand if they are already over these substrates as the tide ebbs. The model is written in ANSI FORTRAN77 and runs in protected mode on a 486 based PC. It includes high resolution runtime graphics and an interactive interface that permits the user to pause and query the model.

Freeman, Gary, and Weissinger, Lisa. (1991). "TABS-2 application to Kawainui Marsh flood control." *Proceedings of the 1991 National Conference on Hydraulic Engineering*, Nashville, TN, July 29-August 2, 1991. American Society of Civil Engineers, New York, 292-297.

The TABS-2 mathematical modeling system was used to evaluate the effectiveness of alternatives designed to eliminate flooding problems in the Kawainui Marsh located in Kailua on the east side of the island of Oahu, Hawaii. The study required unique applications of the TABS-2 modeling system. The verification required altering the numerical

code to model free flow over the existing Federally constructed flood control levee which overtopped during the 31 December 1987 storm event and caused extensive damage to the community of Coconut Grove. One of the alternative plans consisted of placing a series of 15 culverts in the existing levee in order to drain the marsh floodwaters into an extension of the Oneawa channel and release them into the Pacific Ocean. This alternative required the addition of culvert modeling capability to the TABS-2 numerical code. These two applications were further exacerbated by the requirement to use dynamic flow simulations in order to accurately model the effects of various hydrographs. The modeling techniques employed and various model results are presented.

Granat, Mitchell A., and Brogdon, Noble J. (1990). "Cumberland Sound and Kings Bay Pre-Trident and Basic Trident Channel hydrodynamic and sediment transport hybrid modeling; Volume I: Main text and Appendixes A, C, and D," Technical Report HL-90-21, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

A previously verified hybrid modeling system (coupled physical and numerical models) of the Kings Bay/Cumberland Sound estuarine system was used to investigate hydrodynamic and sedimentation variations associated with Trident channel expansion. The models generally demonstrated small velocity differences between the pre-Trident base channel condition and the enlarged Trident channel condition tested. Reduced velocity magnitudes in the deepened upper Kings Bay turning basin demonstrated the largest base-to-plan velocity differences.

Subtle circulation differences were identified. The deepened and widened Trident plan channel increased flood and ebb volume transport efficiency of the submarine channel through St. Marys Inlet into Cumberland Sound and Kings Bay. Increased discharge through the past Kings Bay changed the phasing relationships north of Kings Bay.

Although not an explicit objective of the modeling efforts, tidal effects were examined. The tested plan condition resulted in higher high-water and midtide level elevations in both the physical and numerical models. Variations were close to, but greater than, model detection limits. Low-water elevations between the models were inconsistent. Based on more recent field data, it was concluded that tide range will probably not change as a result of Trident channel improvements, and mean water level in Cumberland Sound may increase a small amount, less than the normal annual variation in mean sea level.

The subtle base-to-plan hydrodynamic differences and the increased plan channel areas resulted in dramatic sedimentation responses. The numerical model predictions indicated a 150 percent increase in required annual plan channel maintenance dredging. Based on previous shoaling history and this study's findings, the typical annual plan channel maintenance dredging requirement is predicted to vary from a low of about 0.9 million cubic yards per year to a high of about 4.9 million cubic yards per year. The long-term average submarine channel maintenance is predicted to increase from approximately 1.0 million cubic yards per year for pre-Trident channel conditions to approximately 2.5 million cubic yards per year for the Trident channel condition.

Granat, Mitchell A., Brogdon, Noble J., Cartwright, John T., and McAnally, William H., Jr. (1989). "Verification of the hydrodynamic and sediment transport hybrid modeling system for Cumberland Sound and Kings Bay Navigation Channel, Georgia," Technical Report HL-89-14, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

A hybrid modeling system (coupled physical and numerical models) was developed to investigate the hydrodynamic and sedimentation processes of Cumberland Sound and the interior Kings Bay navigation channel. The hybrid modeling procedures and the physical and numerical model verifications are described in detail.

The Kings Bay physical model was an accurately scaled fixed-bed concrete model of the Cumberland Sound/Kings Bay estuarine system. The physical model provided the means of assessing three-dimensional hydrodynamic characteristics of Cumberland Sound and Kings Bay. It also provided the boundary forcing conditions for the numerical model and an expanded data base for comparison. Verification of the physical model to reproduce pre-Trident channel field measurements collected during November 1982 and transitional channel conditions measured during January 1985 was demonstrated.

The other component of the modeling system was the US Army Corps of Engineers Generalized Computer Program System: Open-Channel Flow and Sedimentation, TABS-2. TABS-2 is a complete depth-averaged finite element numerical modeling system. The numerical hydrodynamic model RMA-2V used physical model-derived St. Marys Inlet water levels and tributary velocity measurements for the boundary forcing conditions for an average tidal cycle. The numerical model was verified to physical model tidal elevations and depth-averaged velocity data for interior locations.

A wetting and drying algorithm was used to numerically model the extensive marsh and intertidal areas of the estuarine system. Marsh-estuarine circulation interaction and prescribed marsh elevation were found to be important in achieving proper hydrodynamic reproduction. Three separate numerical model schematizations or meshes of the Cumberland Sound system were verified as the submarine channel evolved in detail. RMA-2V demonstrated reasonable reproduction of pre-Trident and transitional channel hydrodynamic conditions for the Cumberland Sound/Kings Bay system.

Hydrodynamic results from RMA-2V were used in the numerical sediment transport code STUDH in modeling the interaction of the flow transport and sedimentation on the bed. Both cohesive (clay and silt) and noncohesive (silt and sand) sedimentation were modeled. STUDH was verified through comparisons of model predictions with actual field shoaling rates. Excellent numerical model pre-Trident channel sediment verification was demonstrated. Model predictions for the upper Trident channel turning basin for the transitional channel demonstrated higher shoaling rates than the limited field data. Possible explanations for this difference included low field sediment loads associated with the prolonged east coast drought, the transitional nature of the channel, and the possible need for further model adjustments. The sediment model was developed and verified for long-

term average conditions, and additional model adjustments could not be justified based on the limited transitional channel data.

Verification of the hydrodynamic and sediment transport hybrid modeling system for Cumberland Sound and Kings Bay navigation channel has been demonstrated. The developed modeling procedures can be used in carefully designed testing programs to assess potential hydrodynamic and sedimentation impacts associated with submarine plan channel and remedial measure alternatives.

Hall, Brad R., and Engel, John. (1995), "Modeling of sedimentation processes in a bottomland hardwood wetland." *Proceedings, International Water Resources Engineering Conference*, San Antonio, TX. American Society of Civil Engineers, New York, 1, 94-98.

For several years, the US Army Engineer Waterways Experiment Station has monitored several physical and biological parameters on the Rex Hancock Swamp on the Cache River for ecosystems modelling purposes. Measurements of suspended sediment grain size, concentration, and deposition quantities within the wetland system were obtained. Boundary conditions and overall sediment budget for the wetland were identified by sampling daily suspended sediment loads at the upstream and downstream limits of the wetland system. The data obtained were then used to develop and test a TABS-MD numerical model of the wetland system.

Hauck, Larry M. (1992). "Hydrodynamics at mouth of Colorado River, Texas, Project; Numerical model investigation," Technical Report HL-92-11, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

The Mouth of Colorado, Texas, Project includes a diversion channel of the Colorado River into the eastern arm of Matagorda Bay, a dam on the present Colorado River channel downstream of the diversion channel, a dam at Culver Cut, and a navigation bypass channel from the Gulf of Mexico to the city of Matagorda, TX. The project will create an intersection of the Gulf Intracoastal Waterway (GIWW) with the navigation bypass channel, which is the emphasis of this study. The freshwater flow diversion is expected to alter existing current patterns and tidal propagation in an area with navigational and recreational concerns.

The US Army Engineer District, Galveston, required that preliminary results from steady-state numerical simulations be produced initially and be followed by field investigations and long-term dynamic numerical simulations of hydrodynamics. Both the field data collection effort and the ship simulation study are described in separate reports.

This report describes the hydrodynamic steady-state preliminary results, verifications to prototype measurements, and long-term tidally influenced simulations using the vertically integrated two-dimensional numerical model, RMA-2V.

Hauck, Larry M., and Brown, Ben, Jr. (1990). "Numerical modeling of hydrodynamics, Brazos Island Harbor Project, Texas (Brownsville Ship Channel)," Technical Report HL-90-5, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

The Brazos Island Harbor Project, south Texas, has been authorized for navigation channel improvements, which include deepening the Brownsville Ship Channel. A vertically integrated two-dimensional numerical model RMA-2V is being used to simulate the Brownsville Ship Channel and the lower Laguna Madre. RMA-2V was used to produce the hydrodynamics (water levels and velocities) for existing and three alternative channel designs. These hydrodynamic conditions were used in a ship simulator study. Historical velocity (direction and speed) measurements taken at approximately hourly intervals during the period 15-18 July 1980 at several stations were used to verify RMA-2V. Water level measurements from 4 tide gages were available for the same period to facilitate model verification. Because the Laguna Madre exhibits large response to wind forcing, some of the inaccuracies in water level verification were suspected to be the result of the sparsity of wind speed and direction data in the prototype system for the model verification. The verified RMA-2V model was operated with a high amplitude diurnal (spring) tide with a temporally varying southeast wind at 4 to 20 mph. The wind was phased to increase both the ebb and flow velocities. With these tidal and wind conditions, RMA-2V simulated the hydrodynamics for existing and 3 alternative channel designs. The peak ebb and flood currents for each design were saved as computer files for use in a separate ship simulator study.

Hauck, Larry M., Teeter, Allen M., Pankow, Walter, and Evans, Robert A., Jr. (1990). "San Francisco Central Bay suspended sediment movement; Report 1, Summer condition data collection program and numerical model verification," Technical Report HL-90-6, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Field data were collected on currents, salinities, and suspended sediments intensively over a lunar day and sporadically over a fortnight in September 1988 for the purpose of identifying transport processes and conditions in central San Francisco Bay and for numerical model verification. Conditions were typical of a low freshwater inflow summer season in this area. A two-dimensional horizontal finite element model was applied and verified to field and physical hydraulic model data. The model is intended for future long-term studies of the fate of dredged material dispersed from the Alcatraz disposal site.

Heath, Ronald E., and Copeland Ronald R. (1989). "Application of two-dimensional model to predict fine sediment deposition." *Sediment Transport Modeling: Proceedings of the International Symposium*, New Orleans, LA, August 14-18, 1989. American Society of Civil Engineers, New York, 118-123.

The TABS-2 two-dimensional numerical modeling system was used to predict the potential for fine sediment deposition in the lock approach channels at Lock and Dam Nos. 4 and 5 on the Red River near Shreveport, Louisiana. This paper outlines the numerical modeling study procedure developed during the Red River navigation study with spe-

cific application at Lock and Dam Nos. 4 and 5. The paper describes the importance of hydrodynamic boundary conditions, sediment concentrations and sizes, and flow durations. The two-dimensional numerical model was very effective for evaluating specific design alteration and their effect on fine sediment deposition in the upstream and downstream lock approach channels.

Heltzel, S. B. (1985). "The impact of the I-664 bridge-tunnel crossing on sedimentation." *Hydraulics and hydrology in the small computer age, proceedings of the Specialty Conference*, Lake Buena Vista, U.S.A., August 12-17, 1985. W. R. Waldrop, ed., American Society of Civil Engineers, New York, Session 4C, 1, 254-259.

The procedures used to study the effects of a proposed bridge tunnel crossing on sedimentation in the James River estuary, Virginia, U.S.A. are briefly described. A finite element hydrodynamic model, RMA-2V was used for a navigation channel study and a general sedimentation study. The non-cohesive or sand version of the finite element transport models of STUDH was used to investigate the navigation channels and evaluate shoaling changes. The cohesive or clay version was used to study the sedimentation. Details of the simulation studies are presented and no adverse impact of the proposed construction was indicated in the channels or in oyster ground areas.

Heltzel, Samuel B. (1988). "I-664 bridge-tunnel study, Virginia; Sedimentation and circulation investigation," Technical Report HL-88-25, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

This report presents results from physical and numerical model tests on the effects of the proposed I-664 James River Bridge-Tunnel complex on (a) sedimentation in the federally maintained channels (Newport News, Norfolk Harbor, and Elizabeth River), (b) general sedimentation in the lower James River, (c) changes in overall flushing characteristics, and (d) changes in current velocities and flushing near the Craney Island disposal site.

The navigation channel sedimentation was evaluated using the TABS-2 finite element numerical models RMA-2V for hydrodynamics and STUDH for sedimentation with an existing numerical mesh of the Elizabeth River and lower James River areas. For the general sedimentation investigation, a new numerical mesh was created and the same numerical models, RAM-2V and STUDH, were used. Data for the flushing and currents evaluation were provided by the Virginia Institute of Marine Science.

Results from the physical model tests indicate circulation changes will be localized with minimal effects on the general circulation of the lower James River.

Results from the numerical sedimentation modeling indicate that sedimentation will be generally unchanged or reduced except on either side of the north island where increases can be expected. The areas experiencing unchanged or slightly reduced sedimentation rates include the oyster grounds, the Elizabeth River and Norfolk Harbor Channels, and the Newport News Channel.

Heltzel, Samuel B., and Granat, Mitchell A. (1988). "Lower James River circulation study, Virginia; Evaluation of Craney Island enlargement alternatives," Technical Report HL-88-8, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

This report presents results from the numerical model investigation whose primary objective was to assess general changes in circulation, currents, and sedimentation associated with six proposed alternative expansion geometries of the Craney Island confined disposal facility. An additional objective of the study was to assess the effects of each of the six alternative geometries on the reported estuarine circulation cell (flow convergence) off Hampton Flats and Newport News Point.

This numerical model investigation used the TABS-2 finite element numerical models RMA-2V for hydrodynamics and STUDH for sedimentation with a modified version of an existing numerical mesh of the Lower James River. Other information presently available regarding the estuarine circulation and flow convergence observed off Newport News Point and Hampton Flats was reviewed.

With the exception of the Newport News Channel, results from the numerical hydrodynamic modeling indicated no plan to base velocity differences greater than ± 0.06 fps at any of the critical areas of interest. Velocity differences greater than 0.10 fps were indicated for the Newport News Channel; channel plan velocities always exceeded base velocities with maximum ebb velocity differences greater than maximum flood velocity differences. Plans with northward extensions resulted in the largest increases. The greatest changes, less than 0.35 fps on ebb and 0.25 fps on flood, were indicated for plans A and B, the largest expansion alternatives also involving westward expansions.

Subtle localized circulation variations, generally within 16,000 ft adjacent to and north and northwest of Craney Island, were identified in base to plan comparison vector plots.

Results from the numerical sedimentation modeling showed that plan to base shoaling index values (plan-predicted sedimentation divided by base-predicted sedimentation) were all within 90 to 110 percent at the critical areas of interest. The Nansemond River entrance was the only area considered to demonstrate any distinct changes in base and plan sedimentation. Considering the existing low sedimentation in the critical areas examined, the indicated differences are well within ordinary field survey detection limits.

Alternatives A, D, and F may impact water quality characteristics as a result of a reduced circulation zone between the Craney Island extension and the mainland.

Appendix A contains general information on the finite element method. A brief description of RMA-2V and STUDH appears in Appendices B and C, respectively.

Heltzel, Samuel B. (1992). "Evaluation of proposed port facilities, Charleston Harbor, South Carolina." *Proceedings of Ports '92*, Seattle, WA. American Society of Civil Engineers, New York, 791-801.

Often it is necessary for port facility designers to evaluate various alternative development plans for port facilities. These evaluations may include a ship navigability study or an evaluation of potential impacts to channel and facility shoaling and maintenance dredging requirements. A study of this type was performed for the South Carolina State Ports Authority (SCSPA) by the US Army Engineer Waterways Experiment Station. The study was designed to provide a preliminary evaluation of two alternative port facilities. This numerical model investigation used the US Army Corps of Engineers

TABS-MD numerical modeling system for open channel flow and sedimentation. Boundary conditions and a verification data set were obtained from the laterally averaged numerical model Fine-Grained Bed Sediment (FIBS). The numerical model mesh used in this study is a comprehensive mesh of the

Charleston Harbor system. Verification was very carefully conducted, and a sensitivity analysis was also performed on model parameters. This paper presents the results of this port facility evaluation.

Hewlett, J. Christopher, Daggett, Larry L., and Heltzel, Samuel B. (1987). "Ship navigation simulator study, Savannah Harbor Widening Project, Savannah, Georgia," Technical Report HL-87-5, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

The US Army Engineer Waterways Experiment Station (WES) ship simulator was used to evaluate the proposed channel widening of the Savannah Harbor from Fig Island Turning Basin to Kings Island Turning Basin. The widening would extend the north side of the channel 100 ft. The present channel width of 400 ft causes difficulties in the maneuvering of the 950-ft New York Class containerhips that began calling in Savannah approximately 2 years ago. For this reason, the simulation study was conducted using a numerical model of this containerhip.

To generate channel currents for input into the simulation, a hydrodynamic finite element model of the Savannah Harbor was developed as part of the study. Boundary conditions for this model were obtained from a larger numerical model of the entire Savannah estuary system developed by the WES Hydraulics Laboratory Math Modeling Group. Prior to testing, professional pilots from Savannah conducted a series of runs for the purpose of validating the simulation.

The simulations consisted of existing and planned conditions. Inbound and outbound runs were performed in opposing currents from an extreme tidal range of 10.5 ft. A total of 42 runs were made, 10 outbound runs in the existing channel, 10 outbound runs in the planned channel, 11 inbound runs in the existing channel, and 11 inbound runs in the planned channel. Professional pilots from the Savannah Pilots Association conned the ship during the tests. Study results were based on a basic statistical analysis in which the means and standard deviations of the following maneuvering parameters in the existing and

planned channels were compared: rudder angle, rate of turn, heading, revolutions per minute, speed, and clearances to the channel edge. Results of this analysis showed a small but consistent improvement in navigation in the planned channel.

Appendix A presents plots of the current model meshes for both the existing and planned channels. Appendix B shows plots of the current vectors from the finite element model. Appendix C shows all pilot track-lines plotted simultaneously for each test condition. Appendix D presents the pilots' ratings of the simulator and of the proposed channel widening and tabulates these comments.

Jones, Norman L., and Richards, David R. (1992). "Mesh generation for estuarine flow modeling," *Journal of Waterway, Port, Coastal and Ocean Engineering*, American Society of Civil Engineers, 118(6), 599-614.

A finite element computer modeling system called TABS-2 has been developed by the U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi. TABS-2 has been used to model shallow water flow in estuaries. Accurate modeling of the flow in estuaries using TABS-2 requires the use of very large two-dimensional finite element meshes. The task of constructing such meshes has traditionally been the most time-consuming and error-prone part of the modeling process. Most automatic mesh-generation schemes are not well suited for estuarine modeling because the regions modeled are typically highly complex and irregular. As a result, the meshes are often constructed manually by coding the mesh in an ASCII file. Manual construction of large meshes is very tedious and can take several weeks to complete. To overcome this difficulty, a mesh generation scheme well suited for estuarine modeling has been developed involving a triangulation algorithm and a variety of mesh editing tools. The scheme makes it possible to generate large meshes of several thousand elements in a relatively short period of time. In addition, the scheme results in meshes with favorable geometric properties, leading to stability and accurate solutions.

Letter, Joseph V., Jr. (1993). "Grand and White Lakes flood control project; Numerical model investigation," Technical Report HL-93-11, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

The Grand and White Lakes flood control project provides protection over a broad portion of the Louisiana coastline. The study area involves a wide variety of wetlands and complex canals and waterways. The area supports many economic interests with potentially conflicting desires for management of the water resources. The project required the capability of quantitatively estimating the relative performance of a large number of design alternatives.

Numerical modeling techniques capable of addressing the flood routing and salinity intrusion processes required to evaluate project alternatives were developed. These techniques included the specification of control structures within the one-dimensional finite element formulation, utilization of marsh porosity, discretization of complex spatial geometric features of the wetlands, and the use of one-dimensional net-

working in conjunction with the two-dimensional finite element formulation.

Numerical testing was performed for eighteen separate design alternatives for the system. Flood events with 2-, 5-, 10-, 25- and 50-year return intervals were simulated and stage exceedance curves generated. Salinity intrusion testing was performed for the influence of marine organism ingress structures on the upstream basin. The results of the testing showed that the marine ingress structures should be very modest in size if salinity intrusion problems are to be avoided. The flood control testing suggested that the optimum location of the increased flow capacity should be near the mouth of the primary tributary, the Mermentau River, or else extensive channelization would have to accompany an alternate location.

Lin, Hsin-Chi J. (1992). "Houston-Galveston Navigation Channels, Texas Project; Report 2, Two-dimensional numerical modeling of hydrodynamics," Technical Report HL-92-7, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

The Houston-Galveston Channel Project consists of about 65 miles of deep-water channels leading from the Gulf of Mexico to the Houston Turning Basin at the head of navigation and Galveston Channel, a side channel from Bolivar Roads to Galveston Harbor. The present channel dimensions are 400 ft wide and 40 ft deep at the mean low tide for most of the channel. The Galveston Channel is 1,125 ft wide and 40 ft deep at the mean low tide.

This study used the TABS-MD numerical modeling system to simulate water levels and currents of different channel design conditions for Houston-Galveston navigation channels. These hydrodynamic conditions were used in a separate ship simulator study.

Water level measurements at six tide gages and velocity measurements taken during a 14-hr survey on 18-20 July 1990 at five current stations were used to verify the model. A different subset of water levels from 20-22 November 1990 were used to further verify the model.

The verified model was used to simulate the hydrodynamics for the existing and two proposed channel configurations of the Houston Ship Channel and Galveston Channel. The peak ebb and flood currents and water levels for each design were used as computer files for use in the ship simulator study.

Comparisons of existing channel velocities with those for Phase I and Phase II of the project indicate slight increases in the lower part of Houston Ship Channel.

Lin, Hsin-Chi J., and Richards, David R. (1993). "Numerical model investigation of Saugus River and tributaries, Massachusetts, flood damage reduction," Technical Report HL-93-5, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

The Saugus and Pines Rivers estuary is located along the Atlantic coast approximately 10 miles north of Boston, MA. Because of the topography and hydraulics of the Saugus and Pines river basins, a big storm

event creates a significant flooding in the areas along the Saugus and Pines Rivers.

A plan was developed by the U.S. Army Engineer Division, New England, to provide flood damage reduction against the Standard Project Northeastern event. The principal component of this plan is construction of tidal floodgates at the mouth of the Saugus River.

The objectives of this study were to use the TABS-MD numerical modeling system to (a) provide upstream and downstream boundary conditions for testing the proposed floodgate plan in a physical model study; (b) determine the impacts caused by breaching of the I-95 embankment at the east branch of Pines River and widened Pines River openings in the I-95 embankment; and (c) evaluate the impacts of floodgate structure on basin tide levels, circulation patterns, and storm surges and sedimentation and the effect of sea level rise on these responses.

Since the proposed floodgate area has not experienced sediment problems, the sediment study was focused on a sensitivity analysis of model parameters. A 24-hr simulation was used to indicate any significant change in sediment deposition and scour pattern in the study area.

The RMA-2V model was successfully verified to limited field measurements including a 3-day field survey of water levels at nine tide gages and a 14-hr survey of velocity measurements at nine current stations. The comparisons of the computed water levels and velocities to field measurements were good.

Breaching of the abandoned I-95 embankment and widening the Pines River opening on I-95 will increase tidal flow in marshy areas. The water levels in marshy areas will increase about 0.5 ft at the peak tide under a spring tide condition. The time lag of the peak water levels between the Broad Sound and upper marshy areas was reduced from 2 hr to 1 hr.

The proposed floodgate will not cause significant change of water levels in the Pines and Saugus Rivers under the normal tide conditions. It will protect the study areas from flooding during the storm events.

The water levels in the marshy areas under Plan 2C+7 will increase about 1.0 ft at the peak flood tide and ebb tide for the 1-ft rise in sea level.

The proposed floodgate will not alter the sediment deposition or scour pattern in the estuary under the normal tide condition, but local scour near the piers may occur.

Lin, H. C., Jones, N. L., and Richards, D. R. (1991). "Microcomputer-based system for two-dimensional flow modeling." *Proceedings of the 1991 National Conference on Hydraulic Engineering*, Nashville, TN, July 29-August 2, 1991. American Society of Civil Engineers, New York, 528-533.

An integrated, microcomputer-based system has been developed for simulation of two-dimensional, unsteady, free surface flows. The system consists of a finite-element mesh generation code, a 2-D hydrodynamic code, and graphical post-processors. The mesh genera-

tion code was specifically designed for interactive construction of irregular meshes and automatic generation of input files to the hydrodynamic code. The hydrodynamic code was adapted from RMA-2 in the TABS-2 system of models. Graphical displays of water surfaces and velocities are presented. The microcomputer-based system provides engineers with a tool that can be applied to various studies of rivers, lakes, and estuaries. System usage and benchmarks for Macintosh and MS-DOS machines is provided. It provides economical and user-friendly desktop applications for most free surface flow problems.

Lin, H. J., Martin, W. D., and Richards, D. R. (1990). "Dredging alternatives study, Cubits Gap, Lower Mississippi River; Report 2, TABS-2 numerical model investigation, Volumes I and II," Technical Report HL-90-20, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

This report presents results from the numerical model investigation whose primary objective was to determine the best method to control shoaling in the navigation channel between Cubits Gap and Head of Passes. The secondary objective was to evaluate the best design configuration for a structural dike plan located at Cubits Gap and the ability of these designs to return the flow distribution to its historical levels.

Several plans were proposed by the US Army Engineer District, New Orleans, and local shipping interests to alleviate the recurrence of these shoaling conditions. They included a sediment trap, advance maintenance, and additional training structures. The first two addressed shoaling problems in the reach between Cubits Gap and Head of Passes. The latter addressed shoaling and flow distribution in Cubits Gap.

This investigation used the TABS-2 finite element numerical model RMA-2V for hydrodynamic analysis and STUDH for sediment transport computation. A large-flow 87-day hydrograph was used to determine the performance of each plan.

Results from the sedimentation modeling showed that the best nonstructural plan was advance maintenance. It provided a smaller quantity of shoaling than the sediment trap plan and affected a smaller area of the navigation channel. Both nonstructural plans, however, would increase the channel shoaling rate compared to existing conditions. For the structural plan, Plan 1 with a 2,800-ft-long angle dike and 800-ft-long headland dike provided the least amount of shoaling of any plan tested. All three dike plans tested would result in a substantial reduction in channel shoaling. Results from the hydrodynamic modeling showed that dike plan 1 returned the flow distribution at Cubits Gap to the amount expected with the supplement II works in place. This study did not address long-term sedimentation effects within Cubits Gap. If one of the structural plans is selected for implementation, a detailed study in the vicinity of Cubits Gap is recommended to optimize the performance of the structure.

Lin, H. C., Jorgeson, J. D., Richards, D. R., and Martin, W. D. (1993). "A comprehensive system for surface water and groundwater modeling." *Proceedings of the Federal Interagency Workshop on Hydrologic Modeling Demands for the 90's*. James S. Burton, compiler, Water-Resources Investigations Report 93-4018, U.S. Department of the Interior, U.S. Geological Survey, Reston, VA

The U.S. Army Engineer Waterways Experiment Station (WES) and Brigham Young University (BYU) have developed a computer interface system that greatly facilitates the pre-processing, execution, and post-processing of watershed, surface water, and groundwater models. The actual computations are made with the models HEC-1 (hydrology), TABS-MD (surface water) and 3DFEMFT (groundwater). A common triangulated irregular network (TIN)-based data structure is used to ensure consistency between hydrology, surface water hydraulics, and groundwater flows. The interface allows easy construction of drainage basins and computes needed input parameters for hydrologic computations and display of hydrographs and flood boundaries. For surface water, the computational meshes and the boundary conditions are easily created and edited. Post-processing tools allow the display of velocity vectors and color-shaded contours of velocity magnitude and water surface elevations in addition to time histories at any point of interest. The groundwater module allows generation and editing of 3-D computational meshes and viewing of results through slices and color contours.

McAnally, W. H. (1987), "Hybrid Modeling to reduce maintenance dredging." *Third United States-The Netherlands Meeting on Dredging and Related Technology*, Charleston, SC, 10-14 September 1984. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

The hybrid modeling approach integrates physical modeling, numerical modeling, and analytical methods to produce results that are superior to other methods of predicting harbor sedimentation. The hybrid method has been described previously, but in brief, it applies each method to those processes for which it is best suited. For example, a physical model is used to describe three-dimensional hydrodynamics. Integrating the various solution methods permits the modeler to take advantage of the strengths of each method while avoiding its weaknesses. In this way, more processes can be modeled more accurately. This study indicates that the hybrid modeling approach, using TABS-2, provides an excellent tool for evaluation plans to reduce navigation channel maintenance.

McAnally, W. H., Jr. (1989). "Lessons from ten years experience in 2D sediment modeling." *Sediment transport modelling; proceedings of the International Symposium*, New Orleans, August 14-18, 1989. S. S. Y. Wang, ed., American Society of Civil Engineers, New York, 350-355.

Examines the work of the Hydraulics Laboratory, Estuaries Division, on two-dimensional models for sediment transport. Applications of the models include studies of navigation channel sedimentation rates, channel morphology changes, erosion/deposition characteristics of open water dredge spoil disposal and changes in suspended sediment concen-

tration (dredging or model) and LAEMSED (width integrated vertical model).

McAnally, W. H. (1989). "STUDH: a two-dimensional numerical model for sediment transport." *Sediment Transport Modeling: Proceedings of the International Symposium*, New Orleans, LA, August 14-18, 1989. American Society of Civil Engineers, New York, 659-664.

TABS-2 water level and flow computations are performed by the generalized numerical model program RMA-2V; salinity and tracer transport computations are performed with RMA-4, and sediment transport computations are performed by STUDH. All three models use the finite element solution technique and can perform computations on the same computational mesh. STUDH performs only sediment transport computations, so hydrodynamics — water levels, current velocities, short period wave heights and periods — must be computed externally and specified as input to STUDH. RMA-2V and STUDH use the same computational mesh and quadratic interpolation functions, so that the water level and velocity field generated by RMA-2V is exactly recreated by STUDH. STUDH calculates transport of sediment by solution of the unsteady, depth-integrated, 2D convection-diffusion equation with source/sink terms representing deposition/erosion processes and bed keeping routines that account for bed structure (thickness, density, strength, etc.) Both cohesive and noncohesive transport are computed.

McAnally, William H., Jr., and Granat, Mitchell A. (1991). "Cumberland Sound and Kings Bay, Pre-Trident and Basic Trident Channel hydrodynamic and sediment transport hybrid modeling; Volume II: Appendix B," Technical Report HL-90-21, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

A previously verified hybrid modeling system (coupled physical and numerical models) of the Kings Bay/Cumberland Sound estuarine system was used to investigate hydrodynamic and sedimentation variations associated with Trident channel expansion. Although not an explicit objective of the modeling efforts, tidal effects were examined. The tested plan condition was predicted by the models to result in higher high-water and midtide level elevations in both physical and numerical models. Variations were close to, but greater than, model detection limits. Comparison of low-water elevations between the models was inconsistent.

This appendix specifically addresses the issue of tidal changes in a compact format. Pertinent information is compared with field observations and analytical considerations.

Based on the presented information, it is concluded that tide range will probably not change as a result of Trident channel improvements. Mean water level in Cumberland Sound may increase a small amount, less than the normal annual variation in mean sea level. It will be extremely difficult to detect any change until data have been collected for several years.

McAnally, W. H., and Stewart, J. P. (1982). "Hybrid modeling of estuarine sedimentation." *Applying research to hydraulic practice, proceedings of the conference*, Jackson, MS, August 17-20, 1982. P. E. Smith, ed., American Society of Civil Engineers, New York, Session 8A, 408-417.

A hybrid modelling method using physical and numerical models in an integrated solution method was developed for use in solving estuarine sedimentation problems. The method was applied to the Columbia River estuary with a large physical model, finite element numerical models RMA-2V and STUDH, a finite difference wave propagation model and several analytical techniques.

McAnally, W. H., Jr., and Thomas, W. A. (1980). "Finite element models in a hybrid model study of estuarine sedimentation." *Finite elements in water resources; preprints of the Third International Conference*, Oxford, MS, May 19-23. University of Mississippi, University, MS.

This paper described how two finite element models fit into a hybrid solution method, and discussed experience gained in their application. Water surface elevation, current velocity, and salinity (in three dimensions) are measured briefly at a number of points in a physical model of the estuary. These measurements are used to drive a finite element numerical model for hydrodynamics—RMA-2. Output from RMA-2 and other models as required (e.g., a wind-wave propagation model) drives a two-dimensional finite element numerical model for sediment transport—STUDH. The several models are connected and complemented by a data management system and several pre- and post-processor computer codes. Present criteria for limits on element sizes, shapes, and time steps appear to be lacking. Rules of thumb and previous experience with what works and what does not are valuable guides, but practical, production-oriented model applications generally require that meshes be stretched to the limit in order to stay within time, cost, and computer resources. A related need is for continuing improvement in computational efficiency—a popular area of endeavor. Recent work made the finite element method competitive with other methods, but further improvements are a necessity.

McAnally, W. H., Berger, R. C., Teeter, A. M. (1993). "Three-dimensional numerical modeling for transport studies." *Proceedings, National Conference on Hydraulic Engineering*, San Francisco, CA. American Society of Civil Engineers, New York, 2, 2141-2146.

Modeling three-dimensional transport of salinity and sediments in estuarine flows requires that hydrodynamics be accurately modeled with sufficient precision to describe the advection and turbulent diffusion of salinity and sediments. These demands are considerably more stringent than those required for modeling water levels and discharges. Application of the model RMA10-WES and TABS-MD system of multi-dimensional models to San Francisco Bay salinity and sediment transport and Galveston Bay salinity illustrates the challenges involved. Residual flows in these bays reflect both density-driven flows, which are strongly three-dimensional, and tidal pumping, which are weakly three-dimensional, and tidal pumping, which is weakly three-

dimensional. Asymmetry in bed stresses combined with these residual flows to induce three-dimensional sediment fluxes that may or may not be consistent with the residual flows.

McAnally, William H., Jr., Brogdon, Noble J., Jr., and Stewart, J. Phillip. (1983). "Columbia River Estuary Hybrid Model studies; Report 4, Entrance channel tests," Technical Report HL-83-16, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

A hybrid modeling approach using a fixed-bed physical model, numerical models, and analytical techniques was used to study navigation channel shoaling at the mouth of the Columbia River. Sixteen plans for reducing channel maintenance dredging at the existing 48-ft depth and at 55- and 60-ft depths were tested. Effects of the plans on tides and currents were found to be subtle. Nondeepening plans had minor effects on salinity intrusion while channel deepening increased salinities by 1 to 6 ppt up to about mile 18. Only one structural plan reduced shoaling below base conditions for the 48-ft channel. Channel deepening increased shoaling considerably.

McAnally, William H., Jr., Brogdon, Noble J., Jr., Letter, Joseph V., Jr., Stewart, J. Phillip, and Thomas, William A. (1983). "Columbia River Estuary Hybrid Model studies; Report 1, Verification of hybrid modeling of the Columbia River mouth," Technical Report HL-83-16, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

The Columbia Hybrid Modeling System was applied to the mouth of the Columbia River estuary to evaluate alternatives for reducing navigation channel maintenance dredging. The hybrid modeling method using a physical hydraulic model, analytical techniques, and various numerical models in an integrated solution method that takes advantage of the strengths of each technique while avoiding its weaknesses. The methods accounted for the effect of tides, freshwater runoff, wind waves, and littoral currents on sediment transport, deposition, and erosion. The models were verified to satisfactorily reproduce observed prototype behavior.

McAnally, William H., Jr., Letter, Joseph V., Jr., Stewart, J. Phillip, Brogdon, N. James, Jr., Anthony, Thomas W. (1984). "Columbia River hybrid modeling system," *Journal of Hydraulic Engineering* 110(3), 300-311.

A hybrid modeling method for predicting waterway sedimentation was developed and applied to the Columbia River Estuary. The method uses physical hydraulic models, two dimensional (2-D) numerical models, and analytical techniques in an integrated solution scheme. The hybrid modeling system used to study the Columbia consisted of a large physical model of the estuary, RMA-2V, a depth-integrated numerical model for sediment transport, and a collection of analytical methods. By using each model to address those phenomena that it is best able to describe, an improved modeling technique is created.

McAnally, W. H., Letter, J. V., Stewart, J. P., Thomas, W. A., and Brogdon, N. J. (1984). "Application of Columbia Hybrid Modeling System," *Journal of Hydraulic Engineering*, American Society of Civil Engineers, 110(5), 627-642.

Describes application of the Columbia Hybrid Modeling System to navigation shoaling problems at the mouth of the Columbia River Estuary, U.S.A. A physical model was used for tidal elevations current speeds and directions at multiple depths and salinity concentrations. The numerical hydrodynamic model RMA-2V was used in conjunction with the physical model. Outlines specification of boundary conditions (slip flows, water surface elevations at nodes etc.). Describes time step and iteration procedures, wave analysis and computation of long-shore (littoral) currents. Five events were used for verification of the model. Sedimentation modelling used the STUDH model. Examines some limitations of the methods used, notably two dimensional treatment of sediment transport. Compares model and prototype dredged volumes, and shoaling pattern (scour and fill).

MacArthur, Robert C., Pennaz, James, Freeman, Gary E., Weissinger, Lisa L., and King, Ian P. (1991). "Enhanced multi-dimensional modeling of marshes and wetlands." *Proceedings of the 1991 National Conference on Irrigation and Drainage*, Honolulu, HI, July 22-26, 1991. American Society of Civil Engineers, New York, 794-800.

This paper summarizes the verification and application of a two-dimensional finite element model capable of simulating the complex circulation characteristics in marshes and wetlands for a variety of boundary and flow conditions. The new 'Marsh Elements and Culvert-Weir' version of computer program RMA-2V includes capabilities to simulate marsh hydrodynamics and culvert and weir flow along the margins of a marsh or wetland.

McCollum, Randy A., and Donnell, Barbara P. (1994). "Claremont Terminal Channel, New York Harbor," Technical Report HL-94-14, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

A ship simulator investigation of Claremont Terminal Channel was performed to determine the effects on ship handling of the proposed widening and deepening of the existing channel from approximately 150 ft to 300 ft and 27 ft mllw to 34 ft mllw, respectively. A hydrodynamic model study of the same area was conducted in support of the ship simulator investigation to supply current fields for the existing channel and proposed channel modifications. This report will describe the ship simulator investigation, its conclusions, and recommendations. Appendix A will describe the hydrodynamic verification and numerical simulation of the existing Claremont Channel bathymetry and two proposed channel design plans. Appendix B describes the governing equations of the TABS-MD numerical modeling system.

Martin, William D., and Berger, R. C. (1989). "Southwest pass training structure alternatives." *Proceedings of the 1989 National Conference on Hydraulic Engineering*, New Orleans, LA, August 14-18, 1989. American Society of Civil Engineers, New York, 969-974.

The U.S. Army Engineer Waterways Experiment Station system of computer programs, TABS-2, was utilized to evaluate various structural plans for increasing channel velocities and sediment transport capacity in the lower Southwest Pass of the Mississippi River. The study area was limited to the lower 4 miles of the Pass. A high flow representing 900,000 cubic feet per second at Venice, Louisiana, was selected for analysis. A high resolution finite element mesh that allowed detailed evaluation of velocity vectors was used to analyze seven alternative plans. This relatively quick and inexpensive analysis technique resulted in an optimal structural plan which provided maximum channel velocities at a minimal cost.

Melidor, Avenant, Thomas, W. A., and McAnally, W. H. (1984). "Numerical model of Mississippi River at Lock and Dam 26." *Water for Resource Development, Proceedings of the Conference*, Coeur d'Alene, ID, August 14-17, 1984. American Society of Civil Engineers, New York, 64-66.

Replacement work was initiated in November 1979. The first stage cofferdam constricted about half of the river channel. As a result, the flow velocity at the construction increased causing considerable erosion, and the river bed dropped about 20 ft during the period of May 1981 to May 1982. The St. Louis District had the Waterways Experiment Station (WES) conduct a physical, movable-bed, hydraulic model study of the scour problem. In addition, the district applied the TABS-2 Numerical Modeling System to the problem with assistance from WES Hydraulics Laboratory personnel. The results of the TABS-2 study are reported. TABS-2 is a system of generalized computer programs and utility programs that are used to model open channel flows and transport processes, including sedimentation.

Pankow, Virginia R. (1988). "San Francisco Bay: Modeling system for dredged material disposal and hydraulic transport,," Technical Report HL-88-27, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

A combination of physical and numerical models was used to simulate the hydrodynamic, circulation, and sediment transport characteristics of San Francisco and San Pablo bays. This simulation was done in response to a request by the US Army Engineer District, San Francisco, to develop a modeling tool that can define the fate of dredged material disposed at the Alcatraz disposal site.

Tide and current velocity data from the San Francisco Bay-Delta physical model were used to verify the vertically averaged hydrodynamic model, RMA-2V (Two-Dimensional Model for Free Surface Flows). This model was used to generate the velocity field for a dredged material disposal model, DIFID (Discharge From an Instantaneous Dump). The suspended sediment concentrations from DIFID and the geometry and hydrodynamic data from RMA-2V were used in the sediment

transport model, STUDH (Sediment Transport in Unsteady Two-Dimensional Flows, Horizontal Plane), to establish sediment transport and dispersion patterns around the Alcatraz disposal site in central San Francisco Bay. Two model meshes were developed for this study: a comprehensive or global mesh of the entire system, and a more detailed inset mesh of the Alcatraz disposal area.

The modeling system has its capabilities and applications. However, the results are just reasonable simulations, not fully verified ones. Each of the numerical models, RMA-2V, DIFID, and STUDH, has individual capabilities and limitations, the greatest of which is the two-dimensional approximation of a three-dimensional phenomenon. The vertically averaged velocities and sediment fields will mask two-layer flow and other three-dimensional processes. Even with this simplification, the model results are useful in estimating the short- and long-term fates of sediments released during a disposal operation.

Appendix A describes the TABS-2 modeling system in which RMA-2V and STUDH belong, and Appendix B gives details of the numerical model DIFID.

Pokrefke, T. J., Jr., Nickles, C. R., Raphelt, N. K., Trawle, M. J., and Boyd, M. B. (1995). "Redeye Crossing Reach, Lower Mississippi River; Report 1, Sediment investigation," Technical Report HL-95-13, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

The sedimentation study conducted on the Redeye Crossing Reach of the Mississippi River about 3 miles downstream of Baton Rouge, LA, was a combination of numerical and physical movable-bed model studies to aid in the development of a satisfactory dike design for this reach. A two-dimensional numerical model, TABS-2, was used to predict the reduction in dredging that could be anticipated with the original dike design and subsequent modifications. Those modifications included changing the length, height, location, and number of spur dikes. The plans investigated addressed the required dike plan to maintain the existing 40-ft navigation channel through the reach and an enhancement of that plan to provide a 45-ft channel to be developed in the near future.

Since no dikes presently exist in this portion of the Mississippi River, the physical movable-bed model study was also conducted to take advantage of the capabilities of both types of models. Thus the overall study allowed use of the numerical model to screen plans and the physical model to address detailed impacts of the plans. The physical model was constructed to a horizontal scale of 1:240 and a vertical scale of 1:200 including the river channel and overbank areas to the adjacent levees. During the overall testing program the numerical model was used to refine and test dike plans. The dike plans deemed most successful from the numerical sedimentation model were also tested on the physical model.

Raphelt, Nolan K., Trawle, Michael J., Weissinger, Lisa L. (1991). "River dike design using a numerical model approach." *Proceedings of the 1991 National Conference on Hydraulic Engineering*, Nashville, TN, July 29-August 2, 1991. American Society of Civil Engineers, New York, 435-440.

The preliminary design of a dike field at Redeye Crossing on the Mississippi River (Baton Rouge, Louisiana) is discussed. The TABS-2 modeling system was used to develop a two dimensional sediment transport model of the Mississippi River from River Mile 228 downstream to 206. Numerical model results are presented. The numerical modeling effort included dynamic simulations two years long to evaluate the impact of proposed dike field layouts on dredging requirements. An assessment of the model's applicability to the design of dike fields consisting of submerged rock dikes and model limitations encountered during the study are presented.

Richards, D. R. (1988). "New Haven Harbor numerical model study," Technical Report HL-88-24, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

This report presents the results from a numerical model study of the impacts of deepening and widening the approach channels and inner turning basin in New Haven Harbor, CT. Results from the study were intended to determine changes in circulation, which might affect valuable oyster resources, and to form the current fields needed to provide a detailed ship simulation study of the navigation improvement project. The US Army Corps of Engineers numerical modeling system, TABS-2, was used to predict the changes that might occur to circulation patterns in New Haven Harbor and portions of Long Island Sound. Currents were predicted in the navigation channel as well as in distant shallow regions where there is a significant shellfish fishery. Results from the numerical model study indicated that there were perceptible changes in the circulation patterns but that the magnitude of the changes was very small. In most cases, base-minus-plan differences in the currents were less than 0.1 fps. The largest differences occurred in the deepened channels, away from the shallow oyster bed areas. No tide differences were detected between base and plan.

Richards, D. R. (1990). "Flow separation around a solitary dike; Eddy viscosity and mesh considerations." *Hydraulic Engineering: Proceedings of the 1990 National Conference*, San Diego, CA, July 30-31, 1990. American Society of Civil Engineers, Boston Society of Civil Engineers Section, Boston, MA, 2, 867-872.

The hydronamic model RMA-2V has been verified on a variety of global circulation studies. These studies rarely involved separated flow patterns around sudden expansions or contractions. This paper presents results from numerical and physical studies of separated flow around a solitary dike. Particular emphasis is placed on eddy viscosity and mesh refinement issues as they pertain to numerical model accuracy.

Richards, David R., Athow, Robert F., and Anderson, Jerry L. (1987).

"Numerical modeling of estuarine training structure effects on navigation channel performance." *Coastal Zone '87: Proceedings of the Fifth Symposium on Coastal and Ocean Management*, Seattle, WA, May 26-29, 1987. American Society of Civil Engineers, New York, 1575-1587.

A two-dimensional, vertically averaged, numerical modeling technique is presented to analyze estuarine training structure performance. The technique consists of using the US Army Corps of Engineers TABS-2 numerical modeling system with special emphasis on high-resolution grids and rigorous model verification procedures. Physical model experimental results are compared with the results obtained from the numerical model simulation for purposes of model verification. A typical estuarine reach of the Columbia River is simulated in the numerical model, modeling both impermeable and permeable dike fields. Excellent numerical simulation of the expected velocity fields was achieved. It is concluded that some secondary currents can be successfully simulated using the required resolution.

Smith, Tamsen M., McAnally, William H., Jr., and Teeter, Allen M.

(1987). "Corpus Christi inner harbor shoaling investigation," Technical Report HL-87-13, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

A combination of numerical models was used to test alternatives for shoaling prevention in Corpus Christi Harbor, Texas. The vertically averaged model system, TABS-2, was used to simulate contributions of sediments by bay waters to the sediment load. The laterally averaged estuarine model, LAEMSED, was used to simulate density currents in the channel and sedimentation that occurs at the harbor entrance.

Applications of the models testing advance maintenance, removal of industrial discharges and withdrawals, advance maintenance in conjunction with a sill, and movement of the disposal areas showed a 20 percent decrease in shoaling as a result of industrial activity removal, a 75 percent decrease in sediments entering the bay channel due to disposal area relocation, and practically no effect on shoaling rates resulting from advance maintenance.

Appendix A presents the results of a reconnaissance survey on shoaling conditions in Corpus Christi Harbor. Appendix B describes the TABS-2 numerical modeling system, and Appendix C describes the theoretical aspects of LAEMSED.

Soong, Ta Wei, and Bhowmik, Nani G. (1991). "Two-dimensional hydrodynamic modeling of a reach of the Mississippi River in pool 19." *Proceedings of the 1991 National Conference on Hydraulic Engineering*, Nashville, TN, July 29-August 2, 1991. American Society of Civil Engineers, New York, 900-905.

A depth-integrated finite-element model (RMA-2V) was applied on a section of the Upper Mississippi River to study the hydraulic characteristics of the flood plain-river system. The area that has been modeled is called 'Montrose Flats.' Aquatic vegetation is abundant at this location, and the flow structure needs to be evaluated in order to

study the nutrient transport conditions within this area. The present study focused on a large oval eddy that was observed to form in this area near the downstream end of the Devil's Creek delta. Causative factors for this eddy were examined by using this numerical model. Results indicate that the eddy can be simulated by this model and that numerical study is a feasible way to examine the mechanisms of eddy formation.

Thomas, William A., and Heath, Ronald E. (1984). "Application of TABS-2 to Greenville Reach, Mississippi River." *River meandering, proceedings of the conference Rivers '83*, New Orleans, LA, October 24-26, 1983. American Society of Civil Engineers, New York, 908-919.

No Abstract

Thomas, W. A., Heath, R. E., Stewart, J. P., and Clark, D. G. (1988). "The Atchafalaya River Delta; Report 5, the Atchafalaya River Delta Quasi-Two-Dimensional model of delta growth and impacts on river stages," Technical Report HL-82-15, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

A quasi-two-dimensional sediment movement computer program was verified to historical bed deposition and scour and used to forecast delta growth for the next 50 years. The results are compared with growth rates predicted by several other methods in Report 6 of this series, "Interim Summary Report of Growth Prediction."

REPORT DOCUMENTATION PAGE

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13. ABSTRACT (Maximum 200 words) <p>The Ashtabula River flows north into Lake Erie at the city of Ashtabula in northeast Ohio. The Federal navigation project in the lower Ashtabula River contains a breakwater protected harbor in Lake Erie and a navigable waterway extending about 3.2 km upstream to a point approximately 300 m downstream of the 24th Street Bridge. Sediments in the harbor and lower 600 m of the waterway are classified as suitable for open-lake disposal, whereas sediments upstream are classified as unsuitable for open-lake disposal. In the harbor and lower 600 m of the waterway, dredging operations are conducted as required to permit commercial navigation. Dredging operations in the remainder of the waterway were suspended in the 1970s, closing the channel to commercial navigation, in response to the increased cost of safe removal and disposal of sediments contaminated with heavy metals, chlorinated hydrocarbons, and polynuclear aromatic hydrocarbons. The waterway is heavily used for recreational navigation. Limited dredging operations were conducted in the reach upstream of the 5th Street Bridge in 1993 to maintain safe navigation conditions for recreational traffic.</p> <p>Numerical hydraulic and sedimentation models of the lower Ashtabula River were developed using the TABS-MD modeling system. The objective of the model study described herein was to estimate the potential magnitude and spatial distribution</p> <p style="text-align: right;">(Continued)</p>				
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of scour that may occur during an extreme event, such as the 100-year return period flood, potentially causing exposure and dispersal of contaminants buried in the channel bed sediments. Other reports in this series describe field data collections and laboratory erosion experiments conducted in support of the model investigation.

The model study revealed that a 100-year return period flood event coincident with Lake Erie stage held at the low-water datum has the potential to scour 80,000 m³ of bed sediments from the lower Ashtabula River producing scour depths generally less than 1 m. The same flood event coincident with a higher Lake Erie stage would produce significantly less scour. The accuracy of model estimates of scour distribution and magnitude are limited primarily by uncertainties in the model data, e.g., erosion rate constant and roughness coefficient, used to describe the natural system.